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The INCA Collaboration: Present status and outlook

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Abstract. The INCA Collaboration develops a new technique based on the ionization-neutron calorimeter combining properties of conventional ionization calorimeters and classical neutron monitors to study local nearby sources of high-energy cosmic rays by measuring the spectrum and composition of the nuclear component in the "knee" region and the spectrum of primary electrons in the energy range 0.1–10 TeV with the proton-background suppression factor up to 10^7. To verify the ionization-neutron calorimeter concept, INCA's prototypes were constructed and exposed to electron, pion, and proton accelerator beams at various energies. Experimental data and simulation results are presented. Perspectives are considered.

1 Introduction

One of the major goals of the INCA Project (Aleksandrov *et al.*, 2001; INCA Collaboration, 1999; Mukhamedshin *et al.*, 2001) is to study the spectrum of primary cosmic-ray (PCR) electrons at $E_e \gtrsim 1$ TeV. The available data are rather poor due to difficulties in separation of electron-initiated cascades against the proton-produced background. To reject electron-like proton-initiated cascades with a high efficiency, we propose to use the fact that the evaporated-neutron yield is much smaller in electromagnetic cascades than in hadron-induced cascades (Bezrukov *et al.*, 1973) .

The second goal is to study the PCR spectrum and composition in the "knee" range ($1-10$ PeV). Space measurements are usually carried out with applying calorimeters designed mainly of heavy substance. We propose, first, to use a light substance (polyethylene, e.g.) that permits to maximize the geometrical factor and, second, to measure energy of primary nuclei by analyzing neutron yield in nuclear-electromagnetic cascades (NEC) in the ionization-neutron calorimeter (INCA).

To analyze these problems, it is necessary both to test experimental modules and simulate processes in an INCA In this work we demonstrate principal potentialities of the INCA related to the problem of primary electron investigation as well as results of measurements of neutron generation in 10-cm thick lead target produced by 43-GeV pions and 26.6-GeV electrons carried out at the U-70 accelerator (Protvino). These measurements are used to calibrate programs of simulations of INCA's features.

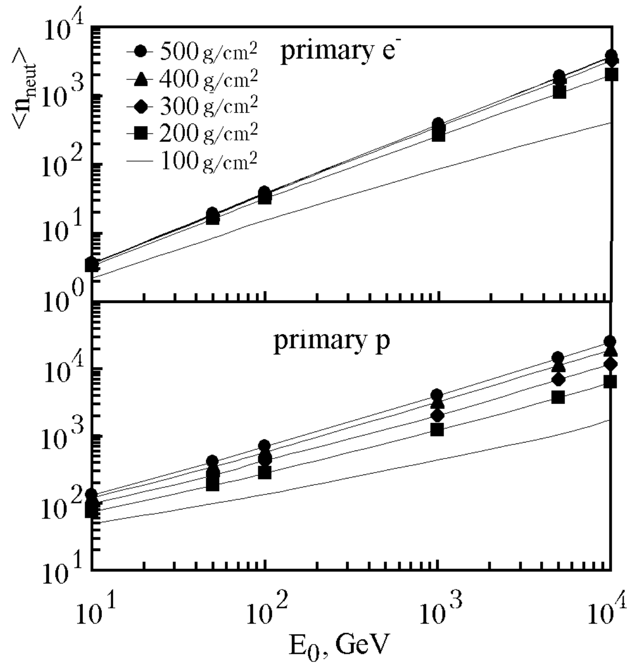

Fig. 1. Energy dependence of the total neutron number $\langle n_{neut} \rangle$ at various INCA's thickness in cascades initiated by electrons and protons.

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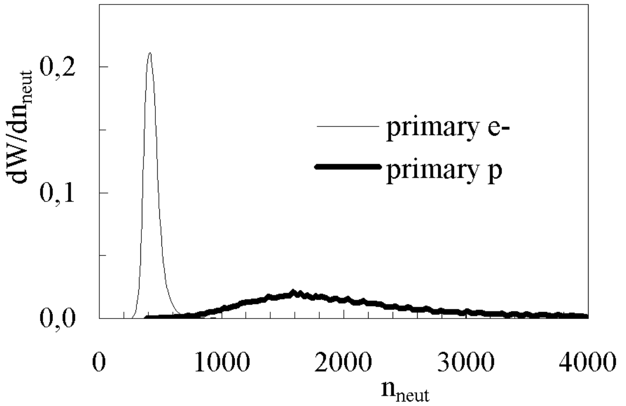

Fig. 2. Distribution of neutron total multiplicity in cascades generated by electrons and protons in INCA with an effective thickness of 300 g/cm^2.

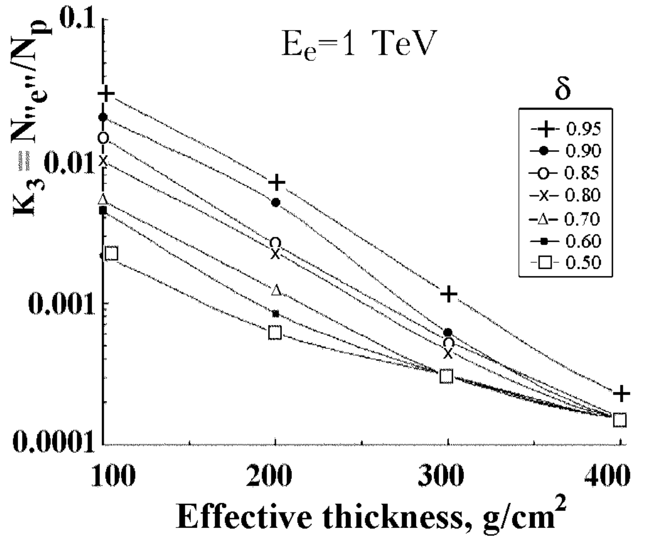

Fig. 3. Rejection factor K_3 for electron-like proton-initiated cascades vs. thickness and electron detection efficiency δ.

2 Separation of primary electrons and protons

Generally, procedures applied to separate electrons can be characterized by two rejection factors $K_1 \simeq 1/20$ and $K_2 \simeq 1/15$ related to

(i) fixing the cascade starting point within the top lead layer and (ii) integral proton spectrum decreasing as $E_p^{-1.7}$.

We suggest a new powerful rejection factor, K_3, associated with the neutron detection.

When accounting for the above factors, we can hereafter consider only proton-initiated cascades which start within the top 10-g/cm^2 lead layer and release the energy $E_\gamma = (0.8 - 1.2)E_e$.

Corresponding simulations were carried out for an INCA with a periodic structure, so that each layer contains lead and polyethylene (10 and 20 g/cm^2, respectively). The lead provides the intense neutron generation, while the light substance provides the nuclear-electromagnetic cascade development. The modified *MC0* code was used (INCA Collaboration, 1999; Fedorova and Mukhamedshin , 1994).

Figure 1 demonstrates the energy dependence of the total evaporated-neutron number integrated over various values of the INCA thickness in electron- and proton-initiated cascades. The difference for cascades of different origin is significant.

Figure 2 demonstrates typical distributions of neutron total multiplicity in cascades generated by protons and 1-TeV electrons at a thickness of 300 g/cm^2. The narrow distribution for electron-initiated cascades does not actually overlap the broad distribution for proton-initiated cascades. This feature is used to reject the later ones and can be described by the rejection factor K_3 which depends on both absorber thickness and the efficiency δ of primary-electron detection (Fig. 3). Here δ is the fraction of electron-initiated events considered after cutting off their distribution's right wing, which could overlap the distribution of proton-initiated events. Even for a thin (100 g/cm^2) setup, $K_3 \approx 10^{-2}$ at $\delta = 0.8$ while at a thickness of more than 300 g/cm^2, $K_3 < 10^{-3}$. One can see that the efficiency of our criterion rather weakly depends on energy.

3 Experiment

To calibrate our programs of calculation of the rejection factor K_3 for INCA's actual types, in the autumn, 2000, measurements of neutron generation in 10-cm thick lead target were carried out at the U-70 accelerator. Fig. 4 shows the experimental device applied for these measurements.

At the same time we solved problems of optimal disposition of neutron counters in the moderator positioned under the calorimeter used in the PAMELA experiment as well as the efficiency of neutron detection in conditions of the PAMELA experiment was found.

A neutron detector with a size of $420 \times 420 \times 150$ mm^3 was applied. The detector contained two polyethylene blocks with a thickness of 60 mm sandwiched by a plate of the same material with a size of $420 \times 210 \times 30$ mm^3 having holes 20 mm in diameter for 24 SNM-17 cylindrical ^{3}He neutron counters (Fig. 4). A lead layer with a thickness of 10 cm (18 radiation lengths or 0.5 nuclear lengths for 43-GeV pions) was placed ahead of the neutron detector.

Preliminary, the evaporation-neutron detection efficiency was determined with the help of a $2.25 \cdot 10^6$-Bq Pu–Be source disposed at various points of the detector prototype. In the detector configuration shown in Fig. 4 (to which data presented below correspond), the average neutron detection efficiency was about 3%. However, the double layer of neutron counters made it possible to elevate this efficiency up to 6%.

The calibration of the neutron detector prototype was performed in the 2B test channel of the IHEP U-70 proton accelerator. Pion (π^-) and electron beams with energies of 43 and 26 GeV, respectively, were used. The hadron admixture

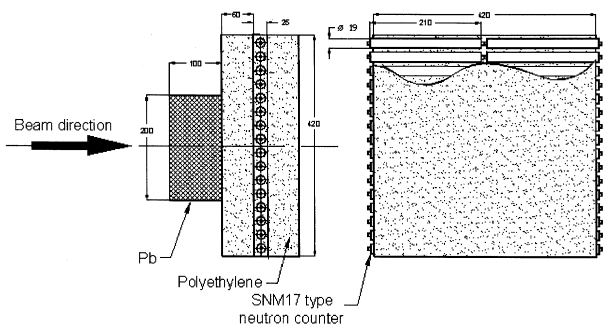

Fig. 4. The INCA's neutron-detector prototype for calibration measurements.

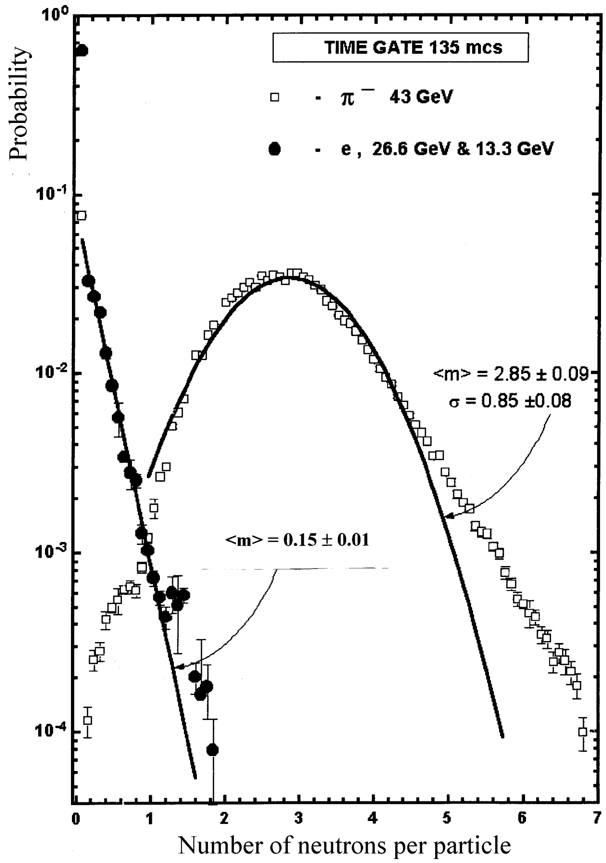

Fig. 5. Distributions of the neutron yield per one trigger for beam electrons and pions.

in the electron beam did not exceed 0.5%. The measurements were performed in the accelerator operation mode with the extended uniform beam extraction during 1.3 s. The total number of particles attained about 10^5 and 10^4 per burst for the pion and electron beams, respectively. The trigger signal was formed by several external scintillation monitors switched in the time-coincidence mode, which were positioned upstream the neutron detector.

Evaporation neutrons emitted by excited nuclei in the thick lead layer at the moment of the high-energy cascade production are thermalized in the polyethylene blocks of the neutron detector for a time on the order of 10 μs. Afterwards, thermal neutrons diffused in the polyethylene, and for times on the order of hundreds of microseconds, their certain fraction was detected by neutron counters, whereas the most of them escape from the polyethylene moderator or were absorbed in it. Therefore, the signal recording in neutron-detector channels occurred within the time gate of 10 to 135 μs, which were open by the external trigger. In the case of the presence of several triggers within the time gate, their number was stored and taken into account in subsequent analysis. Thus, below, the neutron yield is determined per one trigger (i.e., per one primary particle).

It is necessary to note that in the given experiment, a collision point for a primary particle in the target was not fixed. This fact plays no role for primary electrons, since they always interact in the target. At the same time, the probability of a pion to pass through 10-cm lead layer without interaction is rather high ($\sim$ 60%) and should be taken into account.

In the course of the experiment, we determined the average neutron yield as a function of the number of triggers and distributions of the neutron yield per one trigger for beam electrons and pions (Fig. 5).

The results obtained enable us to make the following conclusions:

1. The average number N_n of recorded secondary neutrons per one primary pion (including the passage of pions through the target without interactions) is 2.85 ± 0.09 that corresponds to $\langle N_n \rangle \approx 7$ per one interacting primary pion. With allowance for the neutron detection efficiency of 3%, the average neutron yield per one 43-GeV pion interacting in the thick lead layer attains about 210.

2. The average number of recorded secondary neutrons per one incident 26-GeV electron is considerably lower than for 43-GeV pions and is about 0.15 (Fig. 6). Thus, the ratio of the measured number of neutron signals for pions and electrons (even ignoring pion escape from the target without interaction) attains approximately 20, while in the actual situation, this number will attain about 50, which is even more than it is predicted by our calculations (Aleksandrov *et al.*, 2001).

3. By optimizing mutual disposition of the polyethylene moderator and neutron counters and increasing their number, we can, for the constant detector size and weight to elevate the neutron detection efficiency up to $\sim$10%. This problem necessitates further investigation aimed at formulation of final recommendations for designing the neutron detector.

Fig. 6 shows results of our previous measurements (Aleksandrov *et al.*, 2001) and new data. For comparison, results of other authors as well as results of calculations for infinite thickness with different atomic number are also given. Furthermore, Fig. 6 shows results of calculations for 60-cm thick lead target and our measurements 3-GeV pions and 70-GeV protons. Our new data are recalculated to the 60-cm thick lead target and also shown in Fig. 6. One can see that the

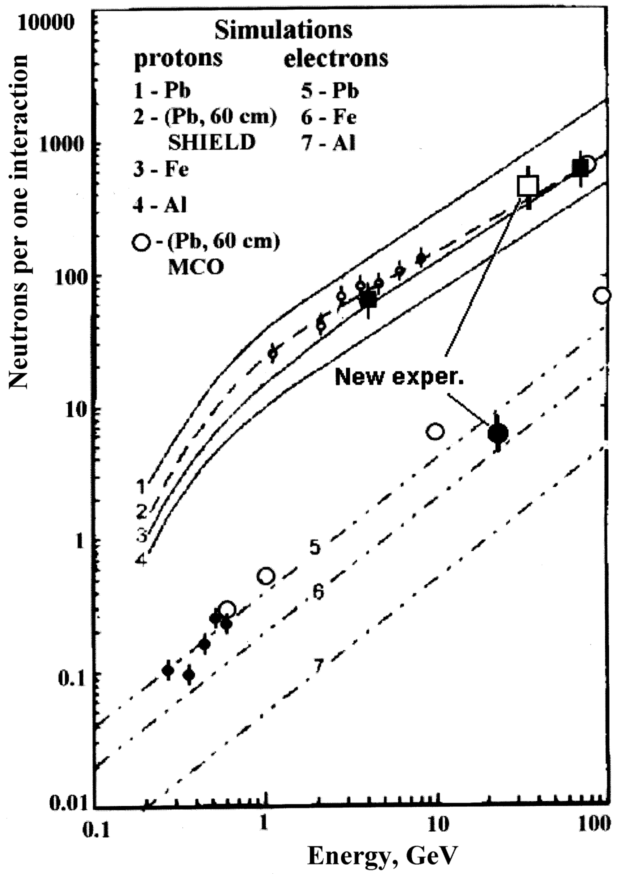

Fig. 6. The average number of secondary neutrons per one incident particles.

π^--initiated neutron yield is in a rather well agreement with calculations made by the *SHIELD* code. The experimental electron-initiated neutron yield is a little lower than that predicted by the *MC0* code. Thus, the experimental difference in neutron yield produced in cascades of different origin is even rather larger than that was predicted by simulations.

4 Outlook

At present the treatment and analysis of experimental data on neutron yield in INCA's prototype accumulated during a spring 70-GeV proton run this year under various angles with respect to the proton beam direction are carried out.

The INCA's full-scale prototype will be irradiated during the nearest autumn (neutron counters and 48 scintillation detector channels with photomultipliers and phototriodes). It is planned (1) to measure both the neutron yield and ionization signals from 26-GeV electrons; (2) to determine the accuracy of primary-particle coordinate measurements by the use of the ratio signal amplitudes at the opposite ends of scintillation detectors; (3) to carry out the detailed comparison of photomultipliers and phototriodes. In this run the cascade's initial points will be fixed at depths of less than 1 radiation length that will improve the definiteness of conclusions on the power of the neutron-yield criterion used to separate nuclear and electromagnetic cascades.

A possible scheme of MacroINCA of 10-t weight and $2 \times 2 \times 2$ m^3 dimensions for space experiments is designed. The main absorber is made from polyethylene and carbon (80% of the total weight) sandwiched by thin ($\lesssim$ 1 cm) layers of plastic scintillator with internal optical-fiber shifters and thin lead layers ($\sim$ 20% of the total weight).

5 Conclusion

A new effective method for separation of primary electrons and protons with a total rejection factor of $\sim 10^{-5} - 10^{-6}$ is proposed to investigate the primary electron spectrum at $E_e > 1$ TeV.

The experimental testing of this method demonstrates a rather excellent agreement with theoretical expectations.

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