The INCA Project IV. New Approach to Measurement of Energy of Primary Protons and Nuclei

The INCA Collaboration

Abstract

New approach to measuring the energy of primary nuclei is proposed on the basis of Monte Carlo simulations. The method of ionization-neutron calorimeter (INCA) is to be used to investigate the spectrum and composition of primary cosmic rays in the "knee" region ($10^{15}-10^{16}$ eV). The method is based on measuring the ionization signal and neutron yield in cascades initiated by primary particles. The new approach permits to use light substances interlayered by thin lead plates. This provides the maximum geometric factor.

1 Introduction

One of the major goals of the INCA Project (INCA Collaboration I, 1999) is to study the spectrum and composition of primary cosmic rays (PCR) in the "knee" region ($10^{15} - 10^{16}$ eV). While at lower energies direct measurements of the PCR spectrum using balloons and satellites are available, the experimental data related to the "knee" range are derived indirectly by extensive-air showers (EAS). As a result, the "knee" problem remains among the central problems of cosmic rays.

Direct measurements of high-energy cosmic rays are usually carried out with applying ionization calorimeters designed mainly of heavy substance that limits dimensions of such devices and, as a result, available energies. To achieve significantly higher energies, it is necessary to use a light substance that permits to enlarge the geometrical factor. Below we consider the main results of Monte Carlo simulation carried out to estimate a possibility to measure energy of primary protons and nuclei by analyzing neutron yield in nuclear-electromagnetic cascades (NEC) in the ionization-neutron calorimeter (INCA).

2 Simulation

We simulate processes in an INCA with a periodic structure, so that each layer contains lead and light substance (polyethylene, e.g.) with a thickness of 10 and 20 g/cm^2, respectively. The lead provides the intense neutron generation, while the light substance provides the NEC development.

A modified version of the MC0 code (Fedorova and Mukhamedshin, 1994), was used, which additionally accounts for (a) approximation B for electromagnetic cascade development; (b) neutron evaporation by excited nuclei due to (a) inelastic interactions of hadrons and γ-rays, and (b) giant resonance processes.

Only the evaporated-neutron generation was considered but not their further behavior. The posterior neutron thermalization and diffusion will be analyzed with using the code SHIELD (Dement'ev and Sobolevskii, 1993). We believe that the results given in the present paper will not be subjected to a qualitative change.

The multiplicity of evaporated neutrons, $\langle n_{neut} \rangle$, per one simulated inelastic hadron/photon interaction with lead nucleus varies with hadron energy from 1 at 10 MeV to $\sim$ 22 at 2 GeV and is actually constant at $E \gtrsim 10$ GeV ($\langle n_{neut} \rangle \approx 26$). This permits to use the neutron signal for energy measurements of primary high- energy particles, when the cascade particle number is sufficiently large.

Below cascades starting within the top 10-g/cm^2 lead layer are analyzed.

3 Results

3.1 Cascade energy determination by ionization signal Potentialities of the INCA in measuring energies of various PCR nuclei of the same energy depends first on dispersion in cascade particle number at a given energy. Figure 1 demonstrates the dependence of the $\sigma(n_{ch})/\langle n_{ch}\rangle$ ratio for the charged particle component integrated over the length of cascades initiated by (a) 10-TeV and (b) 1-PeV primary nuclei on cascade length.

As is seen from Fig. 1, the relative accuracy of energy measurements is low at the initial stage of cascades. However, the standard deviation attains a reasonable value ($\sim 30\%$ for protons and less for nuclei), when the device thickness used for energy determination relates to the cascade maximum ($\sim 200 - 250$ g/cm^2 within the energy range under consideration). Simulations show that the use of initial cascade stage decreases the accuracy. Thus, it seems to be reasonable to use for energy determination mainly the close-to-maximum cascade part.

3.2 Cascade energy determination by neutron signal It is very important that the total amplitude of the evaporated-neutron signal can also serve as an additional information on the primary particle energy. As is seen from Fig. 2, the energy dependence of the total cascade evaporated-neutron number integrated over various values of the INCA thickness initiated by protons is linear in the doubly logarithmic scale in a wide energy range. Nuclei demonstrate a similar behavior.

As is seen from Fig. 3, the magnitudes of differential evaporated-neutron yields in proton- and iron-initiated cascades does not exceed the factor of two beginning from ~ 200 g/cm^2. At small depths the signal highly correlates with primary particle type. The multiple-peak behavior is related to INCA's interlayered structure.

To estimate INCA's potentiality in applying the neutron signal for energy determination, Fig. 4 demonstrate the dependence of the $\sigma(n_{neut})/\langle n_{neut}\rangle$ ratio for the neutron component integrated over the length of cascades initiated by 10-TeV and 1-PeV primary nuclei on cascade length.

As is seen from Fig. 4, the relative accuracy of energy measurements is low at the initial stage of cascades. However, the standard deviation attains a reasonable value ($\sim 30\%$ for protons and less for nuclei), when the device thickness used for energy determination relates to the range behind the cascade maximum ($\sim 300 - 350$ g/cm^2 within the energy range under consideration). Simulations show that similarly to the ionization component, the use of initial cascade stage decreases the accuracy. Thus, it seems to be reasonable to not use the initial stage for energy determination.

4 Conclusion

New method based on measuring the neutron yield is proposed to study the energy spectrum of primary cosmic rays in the "knee" region ($10^{15} - 10^{16}$ eV).

References

Dement'ev, A.V. & Sobolevskii, N.M., Proc. Special. Meeting Intermed. Energy Nucl. Data: Models and Codes (Paris 1993) NEA OECD, 237.
Fedorova, G.F. & Mukhamedshin, R.A., Bull.Soc.Sci. Lettr.Lodz, Ser.Rech.Def. 1994, XVI 137.
INCA Collaboration I, Proc. 26th ICRC (Salt Lake City, 1999), OG 1.2.33

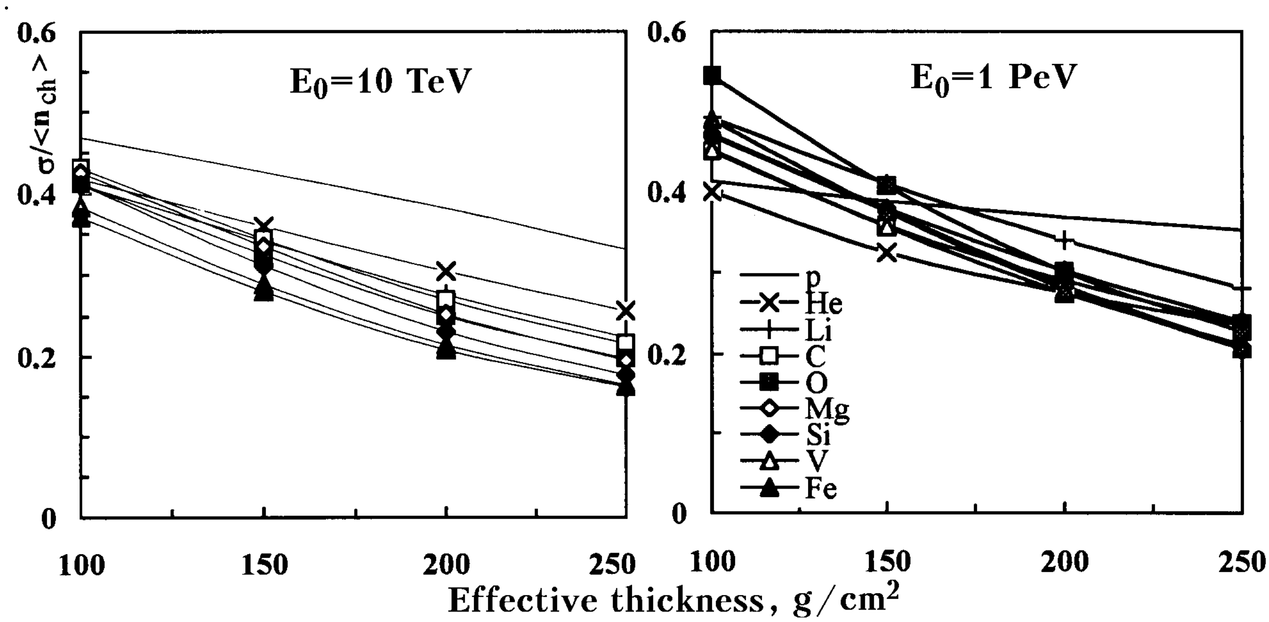

Figure 1: Dependence of the $\sigma(n_{ch})/\langle n_{ch}\rangle$ ratio for the number of charged particles, integrated over the length of cascades initiated by 10-TeV and 1-PeV protons and nuclei, on cascade length.

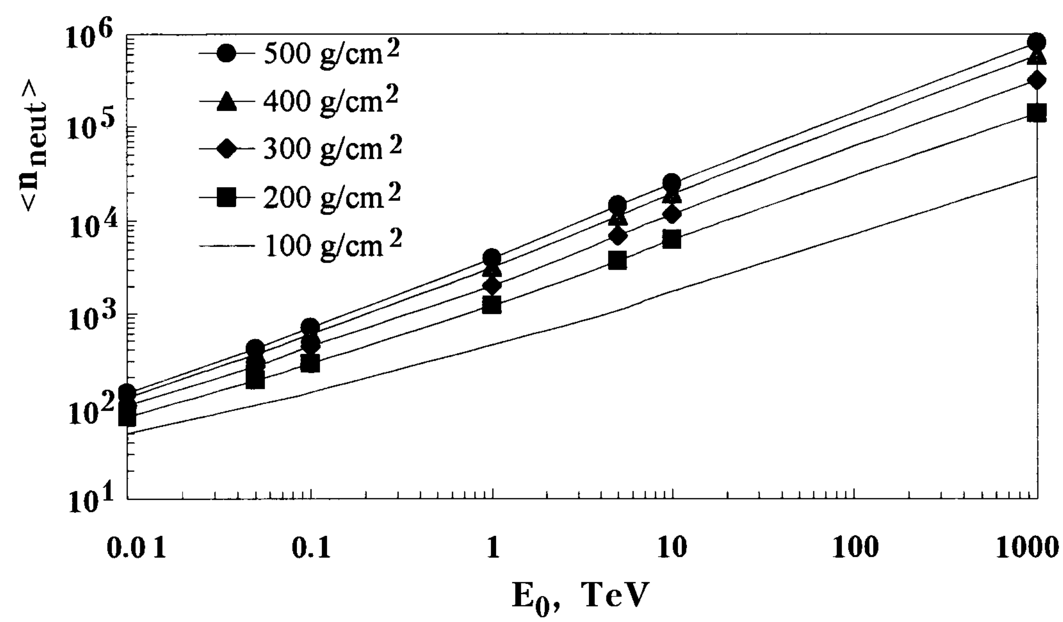

Figure 2: Energy dependence of the total evaporated-neutron number $\langle n_{neut}\rangle$ at various INCA's thickness in cascades initiated by protons.

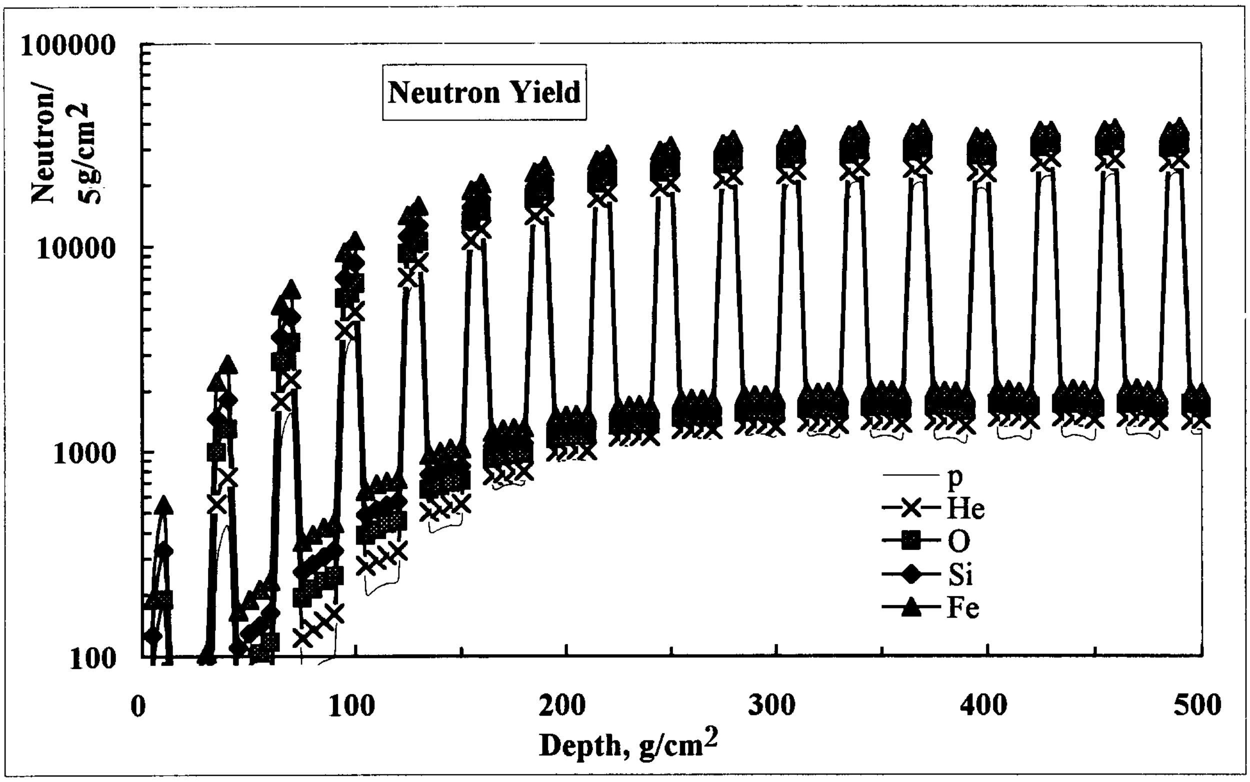

Figure 3: Depth dependence of the neutron yield per 5 g/cm^2 in cascades initiated by 1-PeV protons and nuclei.

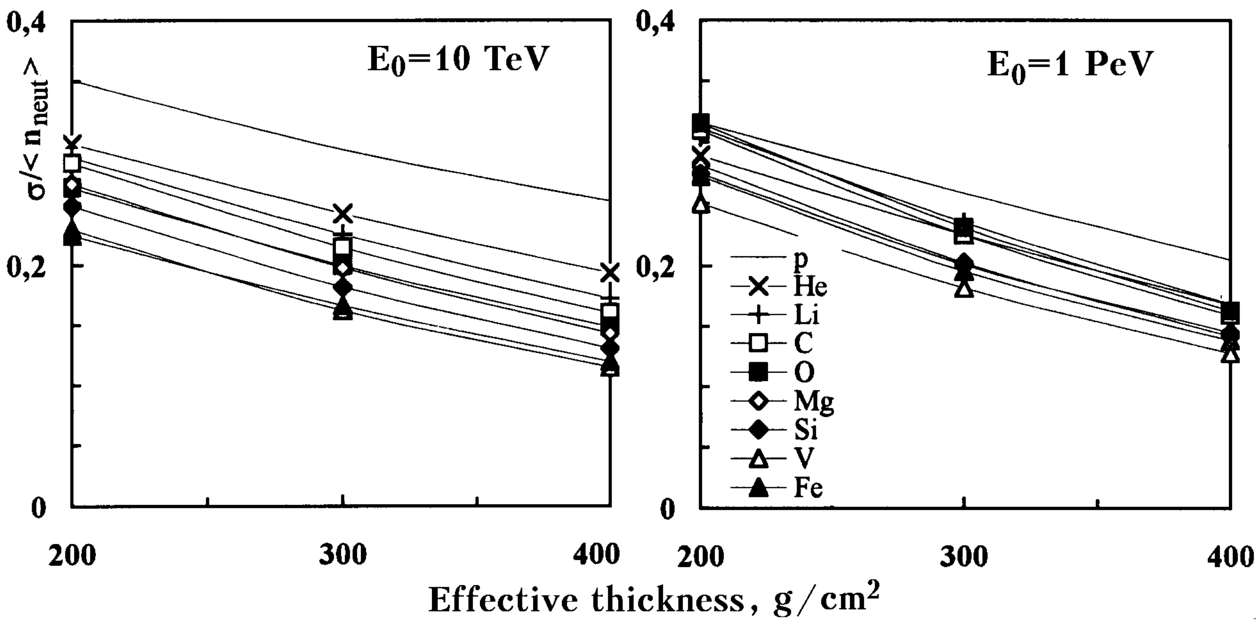

Figure 4: Dependence of the $\sigma(n_{neut})/\langle n_{neut}\rangle$ ratio for the number of evaporated neutrons, integrated over the length of cascades initiated by (a) 10-TeV and (b) 1-PeV protons and nuclei, on cascade length.