Detection of neutrons by delayed ionization in a new type of neutron-ionization calorimeters developed for space cosmic-ray projects

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***Abstract*. The FLUKA code is used to check the method (proposed earlier for the INCA project) of detection of MeV-range neutrons originated in nuclear and pure electromagnetic cascades in multilayer image lead-scintillator calorimeter (with an admixture of cadmium or gadolinium) without neutron counters by delayed ionization. MeV-range neutrons lose their energy during several microseconds in collisions with light nuclei, diffuse, and become captured by Cd or Gd nuclei with subsequent emission of gamma-rays which, in their turn, are converted into electrons. Amplitudes, time windows, a lateral spreading of delayed ionization produced by these electrons in scintillator layers are calculated. It is shown that neutron signal measured by this way can be highly efficient for the separation of electron-initiated cascades from the proton-initiated ones up to energies of several TeV. This method is planned to be used in the new space projects HERO (High Energy cosmic Ray Observatory) and INCA (Ionization-Neutron Calorimeter) aimed at investigation of different species of high-energy cosmic radiation (protons, nuclei, electrons, diffuse gamma-ray emission) with a high accuracy.**

***Keywords*: calorimeter, neutron registration, space project**

I. Introduction

Proposal on high-power supply High-Energy cosmic-Ray Observatory (HERO) is presented in [1]. This middle-weight instrument (2.8 ton) makes it possible to detect nuclei up to $E_0 \simeq 10^{16}$ eV, the energy spectra of electrons at $E_e \simeq 10^{11}-10^{13}$ eV and diffuse γ-ray emission at $E_\gamma < 10^{12}$ eV. The HERO instrument is a new type of 3D image scintillator ionization calorimeter with an absorber from lead and admixture of gadolinium (Gd) or cadmium (Cd). Energy is planned to be measured by using both the ionization and neutron calorimetry techniques. The electron-initiated cascades are hoped to be selected by using neutron-yield counting and cascade-shape analysis approaches as it was proposed in the INCA project [2] (a 12-ton instrument).

The characteristic feature of the HERO calorimeter proposed to decrease the instrument weight is the detection of neutron yield by the same scitillators as main ionization signal. This idea was proposed for the INCA project in [3]. Some doping of cadmium or gadolinium having a large cross sections of capture of thermalized neutrons (σ^{Cd}_{capt}=5300 barn, (σ^{Gd}_{capt}= 60000 barn at $E_n = 1$ MeV) into calorimeter (by using covering paints or foils) results in the emission of a few γ-rays ($N_\gamma = 3-4$) with a total energy of $8-13$ MeV. They give origin to electromagnetic mini-cascades resulting in a measurable amount of some delayed ionization appeared within the time interval $0.1-70$ mcs. When detecting neutron yield, scintillator detectors operate in the counting mode, while the same scintillator detectors must register the ionization component in the amplitude-measurement mode. The schematic view of the delayed-ionization signal in form of pulses produced by secondary neutrons generated initially by one high-energy incident particle is shown in Fig. 1. The time gate is mainly determined by the time needed for MeV-range neutrons (evaporated in collisions of secondary electrons and hadrons in cascades with lead nuclei) to be thermalized and captured by Gd or Cd nuclei. The idea to use gadolinium as a converter of neutrons into γ-rays was first applied in a position-sensitive detector in

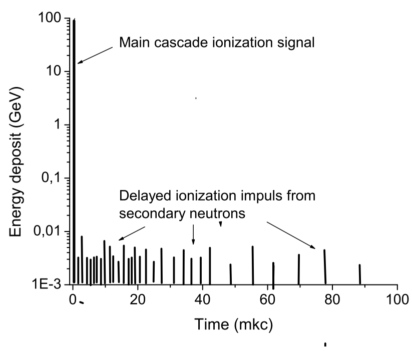

Fig. 1: Schematic view of the signal from incident particle with delayed ionization from secondary neutrons

[4]; besides, the use of gadolinium admixture in water for the detection of neutrons produced in antineutrino interactions is applied in Super-Kamiokande [5].

The aim of this work is to calculate in the framework of FLUKA code [6] the delayed ionization produced by neutrons, to estimate an appropriate time window, amplitudes of signals, lateral spreading of ionization, and to check the difference in delayed ionization produced in electron- and proton-initiated cascades. We concern the problem of energy estimation by the neutron yield in cascades as well.

II. Method of calculation

FLUKA code [6] is used for calculations. On the one hand, it allows us to simulate the particle transport and interactions with matter, and to cover an extended range of lower energy applications spanning from proton and electron accelerator shielding to target design, calorimetry, activation, dosimetry, radiotherapy etc. On the other hand, FLUKA can simulate with high accuracy interactions and propagation in matter of different particles (up to 10 PeV by linking FLUKA with the DPMJET code) including all the corresponding antiparticles, neutrons (down to thermal energies), and heavy ions. For neutrons with energies lower than 20 MeV, FLUKA uses its own neutron cross-section library containing more than 140 different materials selected for different tasks in physics, dosimetry and accelerator engineering and derived from most recently evaluated data:

- ENEA multigroup P5 cross sections.
- Gamma-ray generation and different temperatures available.
- Standard multigroup transport with photon and fission neutron generation.
- Detailed kinematics of elastic scattering on hydrogen nuclei.
- Transport of proton recoils and protons from N(n,p) reaction.
- Capture of photons generated according to the multigroup treatment but transported with the more accurate EMF package which performs continuous transport in energy and allows for secondary electron generation.
- time window for the calculation.

In this work we present the probe variant of calculations of simplifyed device: ionization calorimeter (IC) of almost cubic-form with 1 m side, composed of 50 polystirol scintillator layers 1.8 cm thick alternated with 50 thin lead layers 0.2 cm thick with small admixture of Cd in the form of thin $(10-100$ mcm) layers. The total thickness in the vertical direction corresponds to 2.0 mean free paths for proton interaction (λ_{int}) or 20 radiation lengths.

It is worth noting that we do not consider here in detail the manner of the scintillation light collection. However, we bear in mind the reliable techniques of *Shashlyk* approach [7], i.e., lead-scintillator sandwiches read out by means of Wavelength-Shifting (WLS) fibers passing through holes in scintillators and lead, used in many accelerator experiments, (KOPIO [7], e.g.). For example, with BASF143E-based scintillator and KURARAY fibers, the effective light yield in the KOPIO *Shashlyk* module ($10\times10\times60$ cm^3 of scintilator and lead plates with 140 fibers running through them) at the entrance to the photo-detector may be as large as 60 photons/1 MeV of the incident photon energy [7]. This value depends on many constructive factors, however, we will consider this signal as a reference point.

The following detector responses for the every incoming particle is calculated:

1) Energy deposited in each scintillator and lead layer at different time windows is scored by the option TCQUENCH [6] that sets time cut-offs. The cascade of secondary particles develops in the calorimeter instantaneously (during a few nanoseconds). We denote it below as "Main ionization signal". The delayed energy deposit from secondary neutrons was considered after 100 ns.

2) Neutron balance, i.e., the algebraic sum of outgoing and incoming neutrons for all interactions. These MeV-range neutrons are mostly evaporated in interactions of secondary cascade particles with lead nuclei.

III. Signal from single neutron

We calculate first the energy deposit produced in scintilator layers by a single neutron with an energy of 1 MeV (a typical value for pure e-m cascades) or 10 MeV (the range 1-10 MeV is typical for nuclear-electromagnetic cascades). The isotropic source of neutrons was placed in the center of the calorimeter. We trace the time of ionizaton and the amplitude in every calorimeter layer. The thermalization and diffusion take a few microseconds, however, a cascade initiated by a gamma-ray emitted after the capture of a neutron by a nucleus develops just instantly, so it looks like a pulse, which is characterized by time and amplitude. We observe that 1-MeV neutron creates one pulse in 100% of cases, however, 10-MeV neutron can create two pulses in 30% cases that is connected with reemission of neutrons.

We consider 3 variants of admixture of cadmium coating on the each side of scintillator layers, namely, 10, 30, and 100 mcm.

In Table I the mean detector response to one neutron with energy $E_n=1$ or 10 MeV originated in the center of the calorimeter is presented. As is seen, neutrons with energy 1 or 10 MeV release about $3-3.2$ MeV inside of about 3 scintillator layers, ($\sim$ 1 MeV per one layer). It is worth noting that the total energy of captured γ-rays is $\sim$ 8 MeV ($\sim$ 5 MeV is lost in lead layers). The time distribution of pulses is described by an almost-exponential law with the characteristic time T_0 which strongly depends on cadmium admixture amount, that, in its turn, allows us to vary the time-window length from 10 to 70 mcs. In this case the efficiency of registration varies from $\sim 90\%$ to 99% and reduces to 54%, if any Cd foil is not used. Lateral spreading of ionization

TABLE I: Average detector response to one neutron with energy E_n produced in the center of the calorimeter. First column shows the thickness of Cd foil; E_{dep} is the full energy deposit in N_{lay} scintillator layers. Ef is the efficiency of registration, T_0 is the mean time for capture, H is the characteristic value of lateral spreading of ionization.

Cd foil thickness	E_n	$< E_{dep} >$	σE_{dep}	N_{lay}	Ef	$< T_0 >$, mcs	$< H >$, cm
10 mcm	10 MeV	3.32 MeV	2.46 MeV	3.25	90%	30 mcs	11.9±0.4 cm
30 mcm	10 MeV	3.35 MeV	2.36 MeV	3.20	91%	13 mcs	12.2±0.7 cm
100 mcm	10 MeV	3.20 MeV	2.44 MeV	3.41	89%	7 mcs	13.4±0.4 cm
10 mcm	1 MeV	2.99 MeV	1.95 MeV	3.00	96%	30 mcs	- cm
30 mcm	1 MeV	3.08 MeV	1.94 MeV	3.08	99%	13 mcs	- cm
100 mcm	1 MeV	3.20 MeV	2.00 MeV	3.20	99%	7 mcs	- cm
0.	10 MeV	1.70 MeV	1.53 MeV	1.8	54%	70.0 mcs	11.6±0.8 cm

is fitted by the exponential law with slopes of $10 - 12$ cm. So, one may give next recommendations.
A) To measure delayed ionization signals (that is planned to be read out by WLS fibers running through holes in the scintillator), these fibers should be collected in one bunch (or at list small number of bunches). Each bunch must be connected to one photodetector (all scintillator layers will operate in this case as one neutron detector). However, to collect light produced by charged cascade particles in every scintilator layer, other fibers and other photodetectors should be used.
B) The time window is to be determined by the background in space, height of the satellite orbit and so on.
C) As the signal produced by one neutron is very low ($\sim$ 3.2 MeV), the critical point is the number of neutrons in nuclear-electromagnetic cascades, which can be registered (this item is considered below).

IV. Delayed ionization in proton- and electron-initiated cascades

First of all one should note that the number of produced neutrons is practically proportional to the amount of lead in the calorimeter. However, the larger is the thickness of lead plates, the higher is the calorimeter's weight and "lost" delayed ionization produced by one neutron.

We simulated several groups of protons with energies of 50 GeV–30 TeV and electrons with energies of 17 GeV – 10 TeV incident vertically on the calorimeter. Electrons release full energy in the calorimeter, however, protons release in average only third part.

First of all we present in Fig. 2 a correlation between the real number of secondary neutrons produced during development of cascades in the calorimeter, N_{real}, and measured effective number of neutrons, N_{meas} (that is calculated as total delayed energy deposit in scintillator layers in the time window 100 ns - 70 mcs devided by 3.2 MeV). The dependence of N_{meas} on N_{real} can be fitted by linear fit $N_{meas} = \alpha \times N_{real}$, where $\alpha = 0.7$ and 0.8 for proton- and electron-initiated cascades, respectively. Coefficient α differs in the two cases because neutrons in proton cascades have higher energies ($1 - 10$ MeV vs. 1 MeV in electromagnetic cascades). As a result, the proton-initiated cascades need

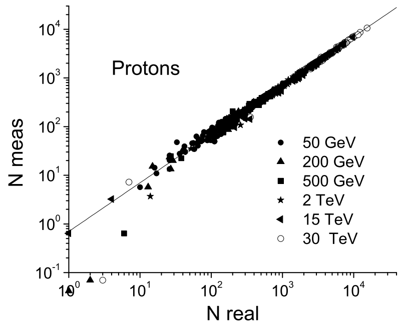

Fig. 2: The correlation of N_{meas} and N_{real} in proton initiated cascades.

more time for neutron thermalization; besides, a part of neutrons leak out through the calorimeter bottom due to the larger depth of maximum in this case.

To compare the delayed ionization in electron- and proton-initiated cascades, we selected only electron-like events among the proton cascades, i.e., cascades, which are produced in upper layers of the calorimeter and have only one-maximum ionization curve.

In Fig. 3 we present the dependence of effective number of neutrons, N_{meas}, "measured" by delayed ionization, on energy deposited in scintilator layers at

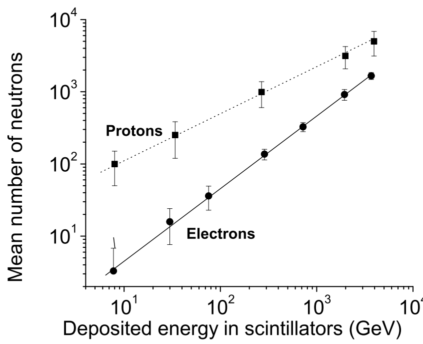

Fig. 3: N_{meas} in dependence on deposited energy in scintillators for incident protons and electrons, error bars denote standard deviations in every point.

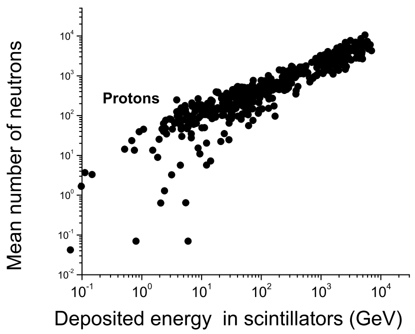

Fig. 4: N_{meas} versus deposited energy in scintillators for individual cascades at 50 GeV - 30 TeV

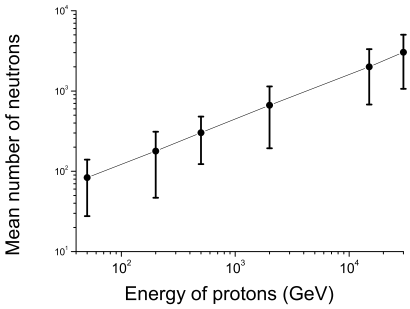

Fig. 5: Mean values N_{meas} and standard deviations (as error bars) for five energy groups of protons at 50 GeV – 30 TeV.

$t < 100$ ns (this value is used in experiment as a measure of energy). One can see that difference in neutron yield is as large at low energies as ~ 35 times. It gradually decreases down to ~ 3 at an electron energy of 10 TeV. Fluctuations of N_{meas} are shown in the Fig. 3 as error bars. The neutron yield for proton-initiated cascades exceeds that for electron-initiated cascades by two standard deviations, that makes it possible to separate protons and electrons at TeV energies.

V. Energy estimation of protons by secondary neutron yield

Neutron yield in nucleus-initiated cascades being proportional to primary particle energy, in principle, can give an independent energy estimation in heavy devices [2]. However, the number of produced neutrons depends very strongly on stage of development of cascades in the calorimeter, so the efficiency of neutron-yield detection for the energy estimation for middle-weight devices like HERO cubic calorimeter is not obvious. In Fig. 4 we present the correlation of energy deposited in scintilator layers and N_{meas} for individual proton-initiated cascades in the energy interval 50 GeV - 30 TeV. Obviously, these variables correlate very strongly with a correlation coefficient of 0.88. So, this method can not be considered as fully independent. In Fig. 5 the N_{meas} mean values and standard deviations (as error bars) are shown for five energy groups of protons. This dependence is fitted as $N_{meas} = 30 \times E_0^{0.63}$ with a relatively small slope value of ~ 0.63, that is caused by lengthening of proton-initiated cascades with increasing energy. The small value of slope leads to worse accuracy of energy estimation by neutron yield in comparison with energy estimation by deposited energy in scintilator layers.

VI. Conclusion

Calculations in the framework of FLUKA code confirm the principal (theoretical) possibility to detect neutron signal produced in cascades in multilayer (100 layers of lead + scintillator plates) calorimeter without special neutron counters by adding some amount of cadmium into calorimeter (as a foil or paint) for the conversion of thermal neutrons into gamma-rays and then, as a result, into electrons. Delayed ionization comprises about $3-3.2$ MeV/neutron being released in about three scintillator layers, with a lateral spreading of ~ 12 cm, the time window $0.1-T_0$, where $T_0 = 10-70$ mcs being strongly dependent on the amount of Cd admixture. When detecting neutron yield, scintillator detectors are planned to be operating in the counting mode. In doing so, all fibers in scintillator layers should be collected into one bunch (or at least into a few bunches) each one being connected to one photodetector.

It is shown that neutron yield measurements can be very efficient for the separation of electron- and proton-initiated cascades at GeV-TeV- energies. However, while the neutron yield in cascades is proportinal to the primary particle energy, the accuracy of energy estimation by neutron yield in relatively thin calorimeter ($\lesssim 2.0\, \lambda_{int}$) is worse than the accuracy reachable by use of usual ionization signal.

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