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Measurement of primary protons and electrons in the energy range of $10^{11} - 10^{13}$ eV in the PAMELA experiment

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Abstract. A spacecraft borne magnetic spectrometer PAMELA is primarily aimed at measurement of antimatter particles with energy up to 2×10^{11} eV or 2×10^{11} eV /n. A modification of spectrometer is proposed to measure the primary protons and electrons in the energy range of 10^{11}-10^{13} eV by addition of a neutron detector, consisting of ^{3}He counters enveloped by a polyethylene moderator. Particle energy is determined from the nuclear-electromagnetic cascades initiated in the PAMELA calorimeter by a primary particle. A separation between the primary proton and electron is implemented through an analysis of the cascade development and an evaluation of number of neutrons recorded in the neutron detector. Calculations show that the system of the PAMELA imaging calorimeter and the neutron detector allows to distinguish the primary electrons with energy 10^{11}-10^{13} eV from the proton flux with a rejection factor up to 10^{-4}.

1 Introduction

The scientific objectives of the PAMELA project primarily included measurement of the (anti)nuclei spectra (from H to C) in the energy range 10^8 eV/n-2×10^{11} eV/n and measurement of the (positron)electron spectrum in the energy range 10^8 eV-3×10^{11} eV (PAMELA collaboration, 1999). Several years ago it was proposed to extend the scope of PAMELA objectives to the study of high-energy cosmic rays. The PAMELA calorimeter (17 radiation lengths or 0.6 interaction lengths in the vertical direction) allows to investigate the particle energy roughly up to 10^{13} eV. That means that primary protons and electrons in a range from 10^{11} to 10^{13} eV could be examined. This energy interval attracts the interest because of two major problems.

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The first problem is a long-standing problem concerning the spectral form and elemental composition of nuclear cosmic ray component with energies 10^{11}-10^{13} eV/n. The problem was initiated by N.L. Grigorov in the late 1960s (Grigorov et al., 1970). It was found that the proton and nuclei spectra differ in this energy interval (Grigirov, 1995; Watson, 1997). Despite the fact that several groups are working in this area (e.g., Ryan et al., 1972; Shibata, 1996; Asakimori et al, 1998; Apanasenko et al., 2001; and references therein) the new observational data are still needed to do a final conclusion. The main difficulty in the interpretation of observational data is the energy range limitation in each given experiment so that peculiarities may be caused by the slight difference in the efficiency of various instruments. The main advantage of the PAMELA instrument is that no adjustment in the absolute flux values will be needed in the 10^{11}-10^{13} eV interval. This energy interval is covered by observational data rather scarcely. Compared to balloon experiments spacecraft borne instruments have the advantages of a long-lasting exposition and an absence of secondary cosmic rays generated in the residual atmosphere. If peculiarities of the cosmic ray spectra in the 10^{11}–10^{13} eV would be confirmed it would mean that there is a source of cosmic rays near the solar system which is responsible for the peculiarity of cosmic ray energy spectrum in the TeV-energy range.

The second problem concerns with search for primary electrons with $E > 10^{12}$ eV. Electrons rapidly loss their energy due to synchrotron radiation and inverse Compton processes, so they cannot come from the far sources and a cut-off in the electron energy spectrum is expected in the case of absence of nearby interstellar sources. Therefore, the discovery of primary electrons with energy above 10^{12} eV will evidence the existence of cosmic ray sources in the nearby interstellar space ($r \leq 300$ pc). It is believed that the main sources of cosmic rays in Galaxy are supernova explosions. There are several supernova remnants in the nearby interstellar space that could produce cosmic rays:

Geminga, Vela, Monogem and others. These remnants are at the distances less than several hundred pc from the solar system. The recent balloon observations (Kobayashi et al., 1999) have recorded 30 electron-like events with E > 8×10^{11} eV, 40 electron events with E>6×10^{11} eV and ~60 electron events with E> 4×10^{11} eV. It is considered as an evidence of close cosmic ray sources. Moreover, if a distance to Vela is about 250 pc rather than 500 pc as it was estimated earlier (Cha et al., 1999) the fluxes of electrons with E > 10^{11} eV should be even higher. The source of high-energy electrons could be Geminga. At the moment of its explosion it was near the solar system at the distance about 30-50 pc (Bignami et al., 1993). The analysis of ^{14}C и ^{10}Be concentration in the stalagmites and in the Antarctic ice supports the hypothesis that a supernova explosion occurred at the distance at ~ 50-60 pc about 3.5×10^4 years ago (Ammosov et al., 1991). The signatures of supernova explosion (5-50)$\times10^4$ years ago at the distance 30-150 pc were revealed in the long-term negative trends of cosmic ray intensity (Stozhkov et al., 2000).

To address these problems a large exposition and ability to distinguish high energy primary electrons against the proton and nuclei background are needed. These requirements are met by a modified PAMELA spectrometer.

2 Facilities for high energy particle measurement

The schematic of PAMELA telescope with the Neutron Detector (ND) is presented in Figure 1.The ND is attached to the bottom of the spectrometer and is situated beneath the scintillation detector S4 that has to trigger the ND in the case of high energy release in the imaging calorimeter. The ND consists of 36 ^3He counters enveloped by a polyethylene moderator and a thin layer of Cd. The weight of the ND is 30 kg.

A high energy particle initiates a nuclear-electromagnetic cascade in the calorimeter allowing the primary energy evaluation. Among other nucleons, neutrons are also generated in a cascade. Afterwards they are thermalized and detected in the ND. The evaporated neutron yield in the hadron-induced cascades is 10-20 times larger than that from electromagnetic cascades (Bezrukov et al., 1973). In addition, the cascades from a primary proton and a primary electron develop in a different way. The joint analysis of the calorimeter and ND information allows to distinguish the primary electrons with energy 10^{11}-10^{13} eV from the proton flux with a rejection factor up to 10^{-4}.

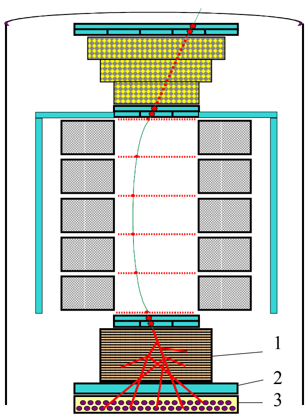

Fig.1 The scheme of the modified PAMELA spectrometer. 1 – the calorimeter, 2 – the scintillation detector S4, 3 – the Neutron Detector.

For the purpose of the study of the high-energy cosmic rays, it is not necessary to examine only those particles coming within the aperture of the PAMELA telescope. The geometrical factor for the omnidirectional flux with exception for solid angle screened by the PAMELA magnet and the Earth is about 900 cm^2 sr. More than 10^4 protons and several hundreds electrons with energy above 10^{12} eV are expected to hit the calorimeter from the lateral directions during a one year exposition. Thus the statistics for three years will be enough to investigate the energy range up to 10^{13} eV.

For a confident evaluation of a primary particle energy, the cascade maximum has to be passed. In this case protons and electrons in the range 5×10^{11}-5×10^{13} eV require ~ 90 g/cm^2 of tungsten. In the vertical direction the total thickness of tungsten in the calorimeter is ~115 g/cm^2, and it can reach ~200 g/cm^2 for lateral directions. Therefore, energy will be determined with certainty for ~15% and ~30% of vertical and lateral protons, respectively. Probability of electron detection is close to 100%.

The Monte Carlo simulation of the nuclear-electromagnetic cascades was performed with the MC0 program (Mukhamedshin, 2000). The proton and electron interactions in the calorimeter were simulated for energies 10^{11}-5×10^{13} eV. Among them the protons that interacted in the first two radiation units from the entrance the calorimeter and released the same energy as an electron would release were considered separately, as they may imitate the electron events (so called electron-like events). We asses an accuracy of particle energy determination in the PAMELA calorimeter as 10-20% in the energy interval of 10^{11}-10^{13} eV.

A finite dynamic range of the strip signal reading system (1400 MIPs) may put an upper limit for the possible energy of an incident particle. According to our estimation, the strip signal of the 10^{13} eV electron still can be resolved satisfactorily. However, this problem needs further consideration, especially for the oblique particles.

3 Neutron yield and detection

Neutron yield in the PAMELA calorimeter was calculated allowing for hadron and photonuclear interactions including a giant resonance. As an example, the result is shown in Figure 2 for energy 5×10^{11} eV. It is seen that a giant resonance gives the main contribution into the neutron yield for a primary electron while hadron interactions are most important for a primary proton.

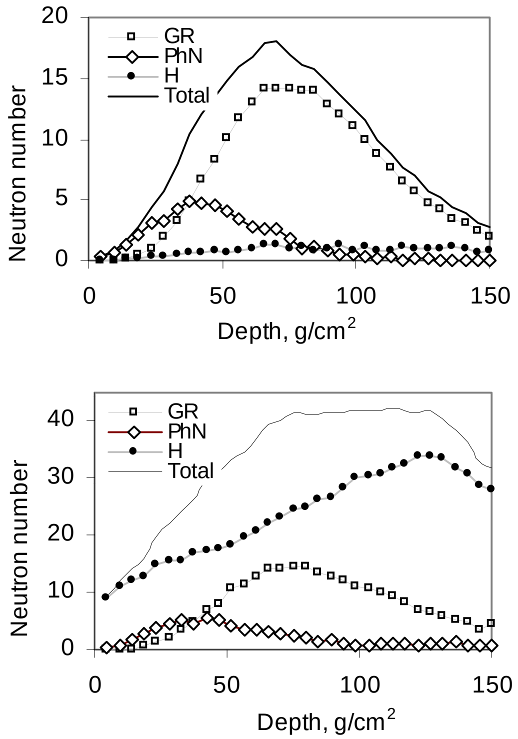

Fig. 2. Upper panel: number of neutrons generated by a primary electron with E=5x10^{11} eV (and its secondaries) at different levels of the calorimeter due to hadron (H), photonuclear (PhN) interactions (without a giant resonance), and a giant resonance (GR). Lower panel: the same as at the upper panel but for a primary proton of the same energy.

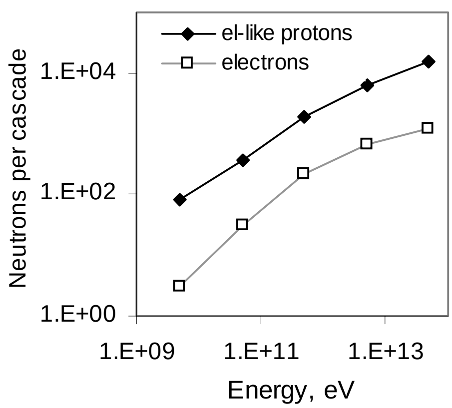

Fig. 3. The total neutron yield summarized over a cascade in the calorimeter versus energy of incident electrons.

Figure 3 demonstrates the difference between the neutron yields for a primary electron and a primary proton imitating an electron event (electron-like proton).

The scintillation counter S4 controls the energy release in the calorimeter and triggers the ND in the case of a high energy interaction occurring. The energy spectrum of evaporated neutrons issued by the calorimeter is presented in Figure 4. The ^{3}He counters are sensitive to the thermal neutrons. The 9.5 cm thick polyethylene moderator provides the detection efficiency for < 1 MeV neutron around 10%.

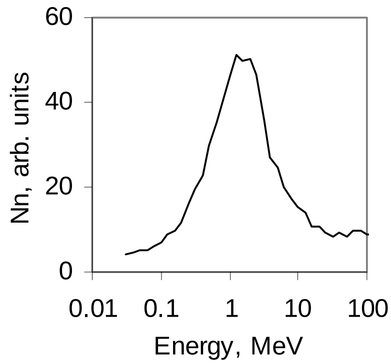

Fig. 4. The energy spectrum of neutrons emitted by the 5 cm of tungsten as a result of high energy interaction.

3 Criteria for electron event selection

The main difficulty in observation of high energy electrons is the much higher fluxes of protons, which should be rejected. The following factors are taken into account. (1) Only the protons initiating a cascade in the first t-units of tungsten will resemble the electrons. The protons that interacted in the first three layers (15.1 g/cm^2) make the rejection factor $K1$ =1-exp(-15.1/185) = 0.08 of the total number of protons passing through the calorimeter. (2) The electron-like proton should release in the calorimeter the same energy as an electron would release. Actually such a proton have to be ~5 times more energetic than an electron because only ~0.2 of the proton energy is contributed to the electromagnetic cascade by inelastic interaction. The number of such protons is $K2$ = $0.2^{1.7}$ = 0.065 times less comparing with electrons because the proton integral spectrum is ~$E^{-1.7}$. (3) The powerful rejection factor is provided by neutron detection. The distributions of the cascades initiated by the primary electrons and protons (with the same energy released into the cascade) over the generated number of neutrons N_n are different. However, they are rather wide, and may overlap to some extent. In this case a primary proton or a primary electron might produce the number of neutrons N_n with a certain probability. The probability for a proton-induced cascade to have the neutron yield less than N_n (i.e. the integrated probability from zero to N_n) is the rejection factor $K3$. On the other hand, the same yield N_n corresponds to the fraction δ of electron-induced cascades with a neutron number ≤ N_n. For δ=95% of electron cascades with the prime electron energy E=5×10^{12} eV $K3$ is around 0.013. For E=5×10^{11} eV $K3$ changes from 0.013 to 0.05 with δ increasing from 50% to 90%.

The total rejection factor $K = K1*K2*K3$. Figure 5 shows the fraction of electron events δ and the total rejection factor for two energy values released into the cascade versus the selected threshold N_{n}.. It is seen that suppression of imitating proton events attains 10^4 for ~95% of electron cascades with primary electron energy above 500 GeV.

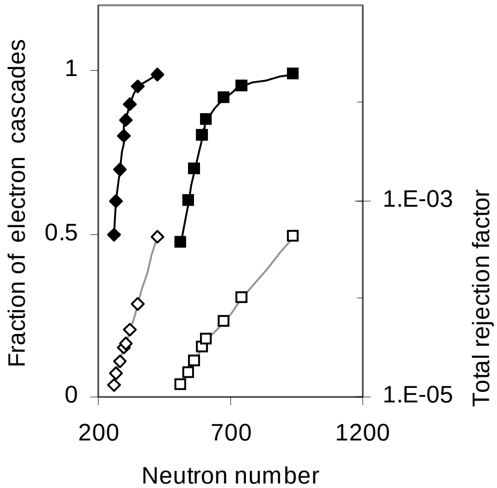

Fig. 5 Fraction of cascades from primary electrons (dark symbols) and the total rejection factor (light symbols) versus the generated neutron number for E = 5×10^{11} eV (rhombs) and E = 5×10^{12} eV.

4 Conclusion

The scope of the PAMELA scientific objectives is extended by including the study of cosmic ray energy spectra in the range of 10^{11} to 10^{13} eV. Augmentation of the Pamela spectrometer by the neutron detector makes it possible to distinguish the primary electrons with energy 10^{11}-10^{13}eV from the proton flux with a rejection factor up to 10^{-4}. Gain in the geometrical factor with the regard for particles incident from lateral sides provides the sufficient statistics for three years of exposition. on the orbit. Thus the modified PAMELA instrument allows to measure electron and proton spectrum in the TeV-energy range and to contribute to solving the question whether nearby cosmic ray sources exist.

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