Search of high-energy solar neutrons by means of large aperture muon hodoscope TEMP

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***Abstract*. A new method of a search of solar neutrons by means of ground-level muon hodoscope TEMP with a high angular resolution (about $1-2°$) is considered. The neutrons may be produced in solar atmosphere by high-energy (E ≈ 10 GeV) protons of the flares or cosmic rays. An excess of the muon flux (about 4 standard deviations) associated with GLE#60 (15.04.2001) is found. Also a small excess of permanent flux of muons ($2.2\ \sigma$) for the calendar period of 230 days, 4 hour expositions daily from the solar direction has been detected.**

***Keywords*: high-energy solar neutrons, solar target**

I. Introduction

High-energy neutrons of solar origin can be produced in two different high-energy physical processes: (i) as a result of short-term proton generation caused by solar flares (emission time of several minutes); (ii) in a continuous process of collisions of galactic protons with the solar atmosphere ($p + N\rightarrow\ n + \ldots$). The direct solar neutrons propagate to the Earth along a straight line, similarly to a ray of light. In the atmosphere of the Earth the reaction of inelastic interaction occurs: $n + N\rightarrow\ \pi + N + N\ldots$ Muons are formed at decays of pions: $\pi\ \rightarrow\ \mu + \nu$. At high energies (few GeV) all three generations of particles are aligned on one ray: $n\ \rightarrow\ \pi\ \rightarrow\ \mu$. Thus, direct solar neutrons create collimated flux of muons (from the direction of the Sun) which can be registered as a small addition to the stationary background of cosmic ray muons. The wide-aperture ground-level muon hodoscope TEMP with a high angular resolution [1] allows observe the phenomena of such type. The minimal energy of neutrons in this process may be obtained from an estimation of ionization losses of energy by muons:

$$T_n > (dE/dx)\cdot\Delta x/\cos\theta, \quad (1)$$

where: $dE/dx\ \approx\ 2\ \mathrm{MeV}/(\mathrm{g}\cdot\mathrm{cm}^{-2})$; $\Delta x/\cos\theta$ is effective way of muons at zenith angle θ. As a result we obtain $T_n > 2$ GeV for vertical registration of muons at ground-level.

II. Method and results

Hodoscope TEMP (MEPhI, Moscow) consists of two pairs of coordinate planes (X, Y) with sensitive area of 9 m^2 and is located at depth 2 m w.e. [1], [2]. The angular resolution is 1-2°. Separate planes are assembled of narrow long scintillator counters-strips (2.5 cm $\times$ 1 cm $\times$ 300 cm). The total number of counters is 512. The hodoscope continuously registers one-minute muon flux as intensity arrays $N_{ik}(t)$ with dimensions 255 $\times$ 255 cells. At any moment, certain zenith and azimuth angles correspond to each element ik [3]. During direct visibility of the Sun the light ray draws some trajectory in pictures-matrices (Fig. 1a).

To exclude the detector geometrical factor and meteorological effects [4], the data are transformed to normalized deviations $n_{ik}(t)$ in each direction ik:

$$n_{ik}(t) = [N_{ik}(t) - f_{ik}(t)]/\sigma_{ik}. \quad (2)$$

The trend of the function $f_{ik}(t)$ is connected with a slow change of muon intensity due to fluctuations of atmospheric temperature and pressure. Fig. 1b shows an example of time series $N_{ik}(t)$ at the fixed cell (ik) which at the moment of time t_0 corrsponds to a solar direction. The smoothed values of $f_{ik}(t)$ in durations from 10 min up to one hour were obtained by different methods, including the median averaging, the weighted average, application of Chebyshev polynomials, etc. The data processing showed that the simple linear smoothing gives the best estimate of approximation and indicated the absence of average value displacement.

Every day in summer time, exposition series of four hour duration (centered at noon) was selected. At this time the Sun was high above horizon, and the effective thickness of the atmosphere in a solar direction was minimal. It must decrease the diffusion of "solar" muon flux due to multiple scattering. To search for effect of high-energy neutron generation, the statistics 1998-2001 years was used.

A. Direct neutrons associated with GLE#60

In association with large solar flare of April 15th 2001 GLE#60, the world net of neutron monitors observed the enhancement of counting rate between 13:35 and 14:30 UT. At this time the aperture of the hodoscope was directed towards the Sun. We also carried out the analysis of data of muon hodoscope TEMP counting rate in this time period from solar direction (Fig. 2). The background level is obtained by taking a running average $\pm$ 45 minutes. About 4 standard deviations ($4\ \sigma$) can be seen at different time points: 13:45, 13:51, 13:57 UT. Data correspond to a time series of two-minute counting rates $N_{ik}(t)$ for cells ($2°\times 2°$). In the work [5] indirect indication of high-energy neutron generation in the GLE#60 event was also obtained.

In this event the minimal energy of neutrons was more

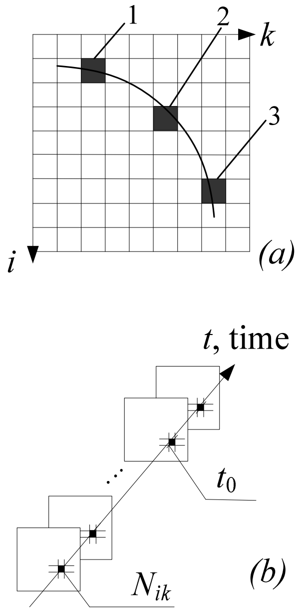

Fig. 1: The “moving” of solar light ray over separate cells of a picture-matrix for different moments of time: (a) – dark square box corresponds to three moments of time (1 – morning, 2 – day, 3 – evening); (b) – the scheme of a sample of time series, including a “solar” cell at the moment of time t_0

than 3 GeV. The direct neutrons could be formed by fast physical processes in solar flare (position S20W85).

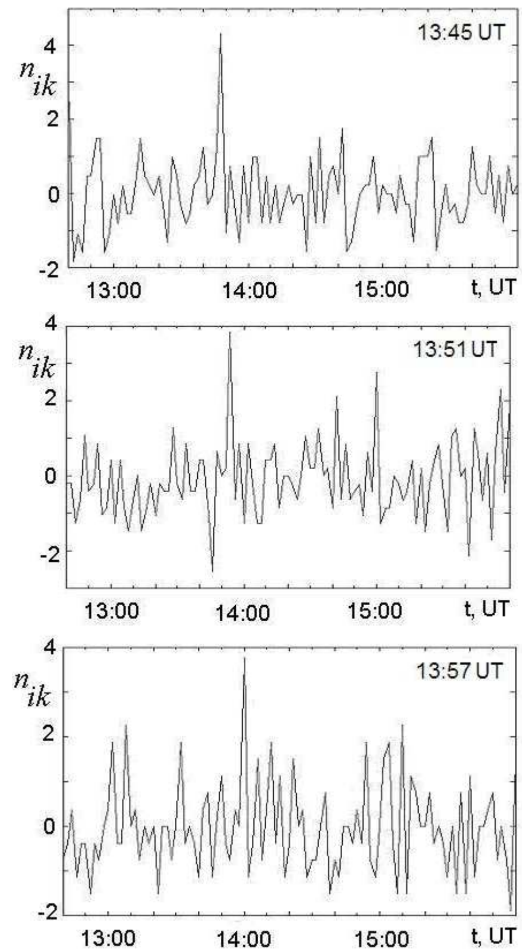

Fig. 2: Two-minute time sequences of muon flux observed by hodoscope TEMP in different angular cells (i, k) during GLE#60. From top to bottom, the panel represents the enhancement around: 13:45, 13:51, 13:57 UT, corresponding to solar direction for these cells.

B. The Sun as a target of cosmic accelerator

In order to search for neutrons from solar target it is necessary to estimate the hodoscope sensitivity to the additional muons flux of the “solar” origin (j^*_μ). The number of “solar” muons must exceed the statistical error of the background cosmic ray muons ($j^{\rm cr}_\mu$) in κ times ($\kappa = 3$ is taken for estimations):

$$j^*_\mu \cdot S \cdot t \geq \kappa \cdot \sigma^{\rm cr}_\mu, \qquad (3)$$

where $j^*_\mu(\text{cm}^{-2}\cdot\ \text{s}^{-1})$ is practically collimated “solar muon” flux; S is the area of ground-level hodoscope; t is the time of exposition in a direction of the Sun. The value of standard deviation $\sigma^{\rm cr}_\mu$ is taken from the flux of background cosmic ray muons:

$$\sigma^{\rm cr}_\mu = \sqrt{N_\mu},\ and\ N_\mu = j^{\rm cr}_\mu \cdot S \cdot t \cdot d\Omega, \qquad (4)$$

where $d\Omega$ is the angular resolution for observation of solar muons. If to take an exposition time for solar direction equal to one year, S and $d\Omega$ as 10 m^2 and $1^\circ \times 1^\circ$, than one can obtain:

$$j^*_\mu = \kappa\sqrt{j^{\rm cr}_\mu \cdot d\Omega/(S \cdot t)} \approx 3 \cdot 10^{-9}\ \text{cm}^{-2} \cdot \text{s}^{-1}. \qquad (5)$$

Also it is necessary to estimate the intensity of neutron flux from the Sun in a direction of the Earth, which is generated on the Sun by isotropic flux of high energy cosmic ray protons (PCR). Fig. 3 shows the scheme of formation of neutron flux in the solar atmosphere. The

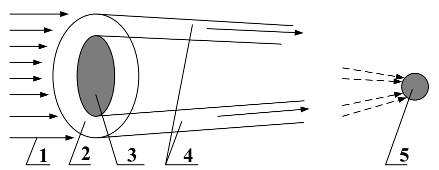

Fig. 3: Scheme of the formation of a beam of neutrons from the Sun: 1 – PCR flux; 2 – effective gas target ΔR; 3 – solar disk ($R_\odot$); 4 – tube of neutron beam in the direction of the Earth; 5 – position of the Earth.

disk of the Sun cannot be used as a target; in this case, PCR particles are completely absorbed and neutrons cannot leave a thick absorber. On the other hand, the target should be enough thick for generation of a large number of neutrons [6]. Optimum target thickness Δx (g/sm^2) along a PCR beam should be of the order of nucleon interaction length ($\Delta x \approx \lambda$). Mainly, neutrons are generated in the photosphere and bottom chromosphere ($\Delta R \approx 10^3$ km), where the density of protons in plasma is high enough $\rho \approx (10^{-8} - 10^{-7})$ g$\cdot$cm^{-3}. Thickness of a generation layer is small and from the Earth it is

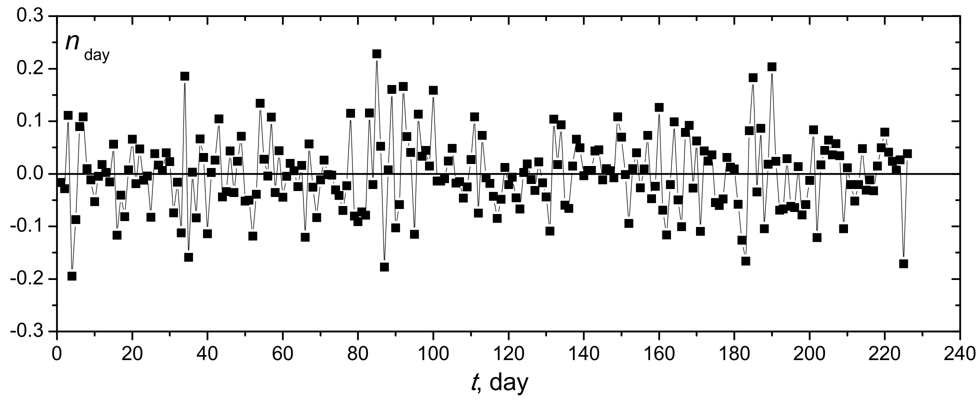

Fig. 4: Dependence of normalized muon flux $n_{\rm day}$ from a solar direction for 230 calendar days (4-hour exposition daily).

seen as a limb with a small solid angle $d\Omega^*$. This angle represents a spherical segment $d\Omega^* \approx 2\pi R_\odot \Delta R / R_{\rm au}^2$, where $R_\odot \approx 0.7$ mln km is the radius of the Sun, $R_{\rm au} = 150$ mln km is the distance between the Sun and the Earth.

The full number of nuclear interactions ($I^*_{\rm nuc}$) in a thin gas solar target can be written in the form:

$$I^*_{\rm nuc}({\rm cm}^{-2} \cdot {\rm s}^{-1}) \approx j_p^{\rm PCR} \cdot d\Omega^* \cdot \left(\frac{\Delta x}{\lambda}\right) \quad (6)$$

where $j_p^{\rm PCR}({\rm cm}^{-2} \cdot {\rm s}^{-1} \cdot {\rm sr}^{-1})$ is PCR flux in heliosphere with several GeV energy; λ is proton interaction length; Δx $({\rm g/cm}^2)$ is thickness of a gas target of the Sun. Estimations show, that $I^*_{\rm nuc} \geq 4 \cdot 10^{-9} {\rm cm}^{-2} \cdot {\rm s}^{-1}$ This means, that the flux of nuclear-interacting particles (including neutrons) from the space accelerator somewhat exceeds the hodoscope sensitivity threshold, and one can hope to register an additional muon flux by means of the setup with a high spatial resolution.

Procedure of data processing consisted in the following:

1) First, the angular position of the Sun for the time moment t_0 was determined.
2) On these data, a time sequence of 1-minute values $N_{ik}(t)$, including as a midpoint value $N_{ik}(t_0)$, was formed.
3) Then values $n_{ik}(t_0)$ for a small interval of time ($t_0 \pm 15$ min) have been calculated.
4) Such processing was consistently repeated for all 4-hour intervals of time (± 2 hour around noon) daily.

As a result, the daily exposition of solar muons included 240 one-minute values of n_{ik} from which the average value $n_{\rm day}$ was defined. At absence of additional muon flux the average value $n_{\rm day}$ should be equal to zero. Positive value means existence of directed flux from the Sun. Similar procedure of calculations $n_{\rm day}$ was carried out for the all 230 days of observations (Fig. 4). The total exposure (four hours a day, 5 m^2 effective area) is about 0.5 year·m^2.

In Fig. 4 it is difficult to note any excess of muon flux. However, the average excess is $\langle n_{\rm sun} \rangle = 0.011 \pm 0.005$. The value of effect (in scale of root-mean-square deviations) has turned out equal to 2.2σ. For estimation of possible imitations of the effect under background conditions (far off the Sun), a similar processing for different time series $n_{ik}(t)$ shifted relative to the Sun by 1.5 hour was carried out. A small value of the background $\langle n_{\rm bac} \rangle = 0.002 \pm 0.005$ (or 0.4σ) indicates the absence of systematic mistakes.

III. Conclusion

Registration of muons at ground-level from processes $N \rightarrow \pi \rightarrow \mu$ allows to study high-energy dynamic processes on the Sun. It is found that among the high-energy particles of GLE#60 the flux of direct relativistic ($T_n \approx 3$ GeV) solar neutrons is also present. The obtained experimental value of the permanent additional flux of muons from the solar direction (at the level of $2.2\ \sigma$) testifies in favor of the possibility of studying the generation of high-energy neutrons in solar atmosphere by PCR protons with energies about 10 GeV by means of ground-level muon hodoscope. This result is obtained during 0.1 year of exposure time.

Acknowledgements

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