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Searching for Solar Neutrons with Energies Lower than 100 MeV in the PAMELA Experiment on Flares of 2006–2014

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Abstract—The results from searching for solar neutrons with energies lower than 100 MeV from solar flares in the period 2006–2014, based on an analysis of the flight data of the PAMELA international space experiment, are presented. The PAMELA neutron detector, based on ^{3}He counters with an area of 0.18 m^2, reveals a solar neutron flux at a level of more than ~300 m^{-2} s^{-1}. Solar neutrons with energies lower than ~100 MeV are likely to be found in 7 of 14 flares between 2006 and 2014.

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INTRODUCTION

The search for solar neutrons with energies lower than ~100 MeV, which cannot be registered by the terrestrial network of neutron monitors, allows us to obtain additional information on processes that occur on the Sun during flares. Due to the instability of neutrons (a neutron's lifetime is 878.5 ± 0.8 s [1], multiplied by the Lorentz factor), ~30% of the solar neutrons with energies of ~100 MeV, ~1% of those with energies of ~10 MeV, and ~0.001% of those with energies of ~1 MeV actually reach the Earth's orbit. It seems likely that neutrons with energies of ~1–8 MeV were first registered by the neutron detector on board the MESSENGER spacecraft at 0.48 a.u. during the flare of December 31, 2007 [2] (a review of the problem is presented in [3]). The PAMELA magnetic spectrometer has a neutron detector for selecting electrons and hadrons, and can be used to search of solar neutrons with energies of up to ~100 MeV during solar flares as well. Neutrons are also generated during all solar flares, and the prospects for their registration depend only on the sensitivity of the registering equipment.

ANALYTICAL APPROACH

We can search for solar neutrons with energies lower than ~100 MeV using the neutron detector of the PAMELA spectrometer in subequatorial sector of its orbit when the Sun is directly visible. Due to the geomagnetic cutoff, only neutrons and the protons of solar cosmic rays (SCRs) with energies above ~10–15 GeV (which are generated very rarely during flares on the Sun) can be registered in the equatorial region. The count of neutrons ~90 min after a flare (the time it takes for neutrons with energies of ~4 MeV to travel from the Sun to the Earth) is compared to the one detected before the flash during PAMELA's previous pass though the equatorial region (shifted ~25° to the east). To allow for the effect variations in the geomagnetic cutoff threshold have on the count rate, the count of the PAMELA neutron detector is determined at practically the same geographic coordinates of two revolutions on the day before measuring the effect. Low-probability variations in the neutron count due to invasive SCR protons are monitored using the PAMELA scintillation telescope.

The count rate of the two planes of the PAMELA neutron detector's ^{3}He counters, surrounded by a polyethylene moderator, is ~6000/min in the equatorial region. When measurements are made over a period of ~10 min, the accuracy of measuring the neutron count with a quiet Sun is ~0.4% of the subequatorial neutron count rate. The count rate of the neutron detector with a quiet Sun is determined mainly by nuclear interactions between galactic cosmic rays and PAMELA's material. There is also a contribution from neutrons of the terrestrial atmospheric albedo. The nature of the count rate of the neutron detector in PAMELA's orbit was investigated by means of GEANTA4 modeling, and was in good agreement with the experimental data.

The detection of reliable additional neutron intensity after a subequatorial flare when the Sun is directly visible, relative to the count with the quiet Sun, indicates the registration of solar neutrons. The energy of registered solar neutrons can be estimated from the time it takes for them to travel from the Sun to the Earth, assuming that the onset of their generation coincided with the flare in the X-ray range (since 499 s is the time it takes X-ray quanta to travel from the Sun to the Earth). This yields a good estimate of the energy range of registered solar neutrons at the steep forward front of the X-ray pulse. According to the GEANT4 simulation data, the efficiency of registering neutrons with energies of ~1–100 MeV using the neutron

Results from the search for solar neutrons in the PAMELA experiment

Flare date	Flare class	Sun region	Energy, MeV	Background effect
13.12.2006	X3.4	S06 W24	~38–96	+1.3 ± 0.7% Yes
07.06.2011	M2.5	S22 W53	~27–40	−1.8 ± 0.8% No
23.01.2012	M8.7	N18 W21	~18–23	+1.5 ± 0.8% Yes
27.01.2012	X1.7	N27 W71	~23–38	+0.2 ± 0.7% No
07.03.2012	X5.4	N17 E27	~3–5	No data ?
17.05.2012	M5.1	N11 W76	~22–27	+1.9 ± 0.9% Yes
06.07.2012	X1.1	S13W59	~11–15	+5.6 ± 1.3% Yes
19.07.2012	M7.7	S13W88	~5–6	+4.3 ± 1.1% Yes
11.04.2013	M6.5	N07E13	~3	No data ?
22.05.2013	M5.0	N14W87	~>100	+4.3 ± 0.7% Yes
06.01.2014	C2.1	S15W89	~9–14	+5.2 ± 0.8% Yes
07.01.2014	X1.2	S12W08	~5–6	−3.7 ± 0.8% No
20.02.2014	M3.0	S15W75	~3–4	−0.2 ± 1.8% No
18.04.2014	M7.3	S20W34	~2–3	−0.1 ± 1.0% No

detector is ~2–3%. The PAMELA neutron detector consists of two layers of ^{3}He counters surrounded by a polyethylene moderator. The neutron detector area is ~0.18 m^2.

MEASUREMENT RESULTS

The PAMELA mission, which started on June 15, 2006, and has now continued for more than eight years, coincided with a period of unprecedented low solar activity. To search for solar neutrons in flares, M and X-class flares accompanied by SCR proton fluxes with energies greater than 100 MeV and above ~10^4 cm^2 sr day were selected using our method and the data from GOES satellites. In the end, 14 flares were selected for analysis between 2006 and 2014. The characteristics of the selected flares and the results from our search for solar neutrons are presented in the table.

CONCLUSIONS

The results from our search for solar neutrons with energies lower than ~100 MeV, based on an analysis of the neutron detector data from the PAMELA magnetic spectrometer for 2006–2014, lead us to believe that solar neutrons were observed with a reliability of 2–4 standard deviations in the flares of December 13, 2006 (~38–96 MeV); December 23, 2012 (~18–23 MeV); May 17, 2012 (~22–27 MeV); July 6, 2012 (~11–15 MeV); July 19, 2012 (~5–6 MeV), May 22, 2013 (~100 MeV); and January 6, 2014 (~9–14 MeV). The effect was not observed in five flares, and none of the information required for analysis was recorded for two flares. Allowing for the energy dependence of the efficiency of neutron registration using the neutron detector, the sensitivity threshold of our search for solar neutrons is estimated to be ~300 (m^2 s)$^{-1}$. The maximum registered effect in our search for solar neutrons corresponded to a neutron flux of ~1800 (m^2 s)$^{-1}$. In the future, we may conduct an additional search for solar neutrons from flares near the west limb of the Sun with a strong X-ray signal and a weak SCR flux registered in terrestrial orbit.

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