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The World Neutron Monitor Network as a tool for the study of solar neutrons

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Abstract. The use of the World Neutron Monitor Network to detect high-energy solar neutrons is discussed in detail. It is shown that the existing network can be used for the routine detection of intense sporadic solar-neutron events whenever they occur. A technique is suggested involving the weighted summation of responses of separate monitors to solar neutrons. It is demonstrated that the use of this method improves the significance of solar-neutron event detection. Different results of the simulation of the neutron-monitor sensitivity to solar neutrons have been tested with respect to their application for practical use. It is shown that the total number of neutrons with energy above 300 MeV injected from the Sun during a solar flare can be estimated directly from the time-integrated neutron-monitor response to solar neutrons without any model assumptions. The estimation technique has been developed.

1 Introduction

Ground-based neutron monitors (NMs) are widely used for registration of the nucleon component of cosmic rays in the Earth's atmosphere. An NM detects, with high efficiency, secondary nucleons produced by cosmic rays in the atmosphere. Throughout the paper, we use the words "NM detects galactic/solar particles" in the sense that we consider the system NM/atmosphere as one entity. At present, there is a worldwide network consisting of about 70 cosmic-ray stations equipped with NMs of different types. In this paper the network is called the World Neutron Monitor Network. There are two main types of NMs in operation: the IGY monitor and the NM64 monitor (Hatton, 1971). NMs detect the Galactic component of cosmic rays (GCR). In addition, the NM can detect solar cosmic rays (SCRs) with energies above several hundred MeV/nucleon. During the last three solar cycles, more than 50 ground-level enhancement (GLE) events caused by SCRs were observed by the World Neutron Monitor Network (Shea and Smart, 1990; Stoker, 1994).

It is very important for solar-physics research that the network can detect high-energy neutrons produced in the solar atmosphere during solar flares (e.g. Takahashi, 1989; Debrunner, 1994). Such neutrons are produced in nuclear reactions of high-energy particles with energies from several hundred MeV/nucleon to several GeV/nucleon with the matter of the solar atmosphere. Therefore, observations of solar neutrons offer a unique opportunity to study energetic nuclear processes as well as particle acceleration processes occurring during solar flares. Today, about ten reliably detected solar-neutron events (SNEs) are known. Two of the events were observed by several NMs during the solar flares of 3 June 1982 (Debrunner *et al.*, 1983; Efimov *et al.*, 1983; Iucci *et al.*, 1984) and 24 May 1990 (Shea *et al.*, 1991; Debrunner *et al.*, 1993; Kovaltsov *et al.*, 1993).

The goal of the present paper is to study the feasibility of the World Neutron Monitor Network as a tool for the investigation of high-energy solar neutrons. Unfortunately, the simulations of NM sensitivity to solar neutrons carried out by different research groups differ significantly from each other (see Sect. 5). Moreover, at present there are no practical ways to calibrate the atmosphere/NM system. Hereafter, the sensitivity concept includes both the instrument and the atmosphere above it. In the present paper, we tested the sensitivity by means of SNEs which were detected with high significance and reliability by different NMs. We also used data of neutrons and γ-rays observed by spacecraft in the interplanetary space. The use of these data allows one to estimate the neutron flux before it enters the Earth's atmosphere and facilitates a comparison with the system's response.

In Sect. 2 we discuss some special features of solar-neutron detection by ground-based neutron monitors.

Further, in Sect. 3, the extraction of a weak signal of information from a high background "noise" is studied with particular emphasis on neutron monitors. Empirical expressions, which describe angular and altitude dependencies of the sensitivity of a neutron monitor to solar neutrons, are studied on the basis of observations of the neutron event of 24 May 1990. It is shown that the expression given by Kovaltsov *et al.* (1993) is in good agreement with observational records, and that the current NM network can be used for continous monitoring of solar neutron events.

The utilisation of useful information not only from a single monitor, but from the whole NM network as well, offers an improvement of the means for the detection of SNEs. In Sect. 4 the technique of weighted summation applied to NM responses is suggested. It is shown that the use of the method improves the significance of the detection of SNEs.

The results of the sensitivity simulation carried out by different groups differ from each other in both integral normalisation and the energetic dependence of the sensitivity in the energy range below 300 MeV. In Sect. 5 we make a test of the normalisation of the NM sensitivity by means of the solar flare of 3 June 1982 and show that the results by Debrunner *et al.* (published in Chupp *et al.*, 1987) for the IGY-type monitor and by Efimov and Terekhov (1988) for the NM64 monitor are in a reasonable accordance with the observations. However, a new numerical simulation of the atmospheric nucleon cascade processes is still apparent. Although the question about the sensitivity of an NM to neutrons with energy below several hundred MeV is still open, it is shown in Sect. 6 that the main contribution to the NM response is due to neutrons with energy above 300 MeV.

Also in Sect. 6 of the paper we study the relationships between the detected response of an NM to an SNE and the characteristics of neutrons injected from the Sun towards the Earth during the event. It is shown that the total number of those solar neutrons with energy above 300 MeV can be obtained directly from the time-integrated NM response irrespectively of the neutron energy spectrum. We calculate the normalisation curve which allows one immediately to calculate the total number of the solar neutrons (> 300 MeV) from the monitor response to neutrons. The accuracy obtained for the number of neutrons is enough for the purpose of solar-flare studies and for testing different models.

Section 7 presents remarks on problems and perspectives of the study of solar neutrons by means of the World Neutron Monitor Network.

2 Preliminary remarks

One of the main difficulties encountered so far in the detection of high-energy solar neutrons by means of a neutron monitor is the weakness of the informative signal with respect to the background level N_b, which is caused by GCR. The mean value of N_b depends on geographical coordinates and altitude of the NM location, and can be roughly described by the following approximate relationship:

$$N_b = N_o \cdot r \cdot f(P_c) \cdot \exp\left(\frac{-\kappa - 1033 g \cdot \mathrm{cm}^{-2}}{\lambda_{CR}}\right) \cdot \Delta t, \qquad (1)$$

where $N_o \approx 70$ counts/s is the average count-rate of a 6NM64 high-latitude sea-level NM (Debrunner, 1994); $f(P_c) \propto (1 - \exp(-aP_c^{-k}))$ is the function taking into account the latitude effect (see Stoker, 1994), where P_c is the geomagnetic cut-off rigidity at the NM location; $\lambda_{CR} \approx 140$ g/cm^2 is the average attenuation length of cosmic rays in the Earth's atmosphere; κ is the atmospheric depth (g/cm^2) at the NM location; Δt is the data collection time; $r = n/6$, where n is the number of counters in a NM64-type monitor. For a comparison of count-rates of different types of NMs it is necessary to know the ratio R of the integral efficiencies of the standard 6IGY and 6NM64 monitors, which depends slightly on time as well as on altitude and location of the NMs. For an IGY-type monitor, the expression for the factor r in Eq. (1) is $r = n/6 \cdot R$, where n is the number of counters. In papers by Hatton and Carmichael (1964) and Hatton (1971) a value of $R = 0.05$ is given for the high latitude and sea level, and this value is usually used when comparing count-rates of different monitors. On the other hand, low-latitude Jungfraujoch (Debrunner *et al.*, 1987) and Haleakala (Pyle, 1993) mountain stations are equipped with counters of both types. The ratio of background count-rates of different types of monitors from these stations corresponds to the value of $R \approx 0.07$.

A dispersion σ_b^2 of the background is determined by assuming random, normally distributed fluctuations of the background count-rate. One can consider the dispersion in the form $\sigma_b^2 \approx mN_b$, where the value of m can be from 1.4 to 4 depending on the geomagnetic cut-off rigidity and the atmospheric depth at NM location. The value of m corresponds to the multiplicity of registration of the secondary cascade nucleons (Iucci *et al.*, 1984). In most cases, one can take $\sigma_b^2 \approx 2N_b$ (Belov *et al.*, 1987).

In a general case, the mean error σ, of a NM count-rate can be written in the form:

$$\sigma^2 = \sigma_s^2 + \sigma_b^2 + \zeta^2, \qquad (2)$$

where σ_s^2 is the dispersion of the signal, σ_b^2 is dispersion of the background, and ζ^2 takes into account other sources of the error (instrumental errors, systematic errors, etc.). Usually, the duration of an SNE is from several minutes to several tens of minutes. One can consider the value of N_b to be constant during such a period. However, in the case of a longer event it is necessary to take into account the possibility of a count-rate trend. The values of σ_s and σ_b are determined by assuming normally distributed random fluctuations of NM responses to solar neutrons and cosmic rays, respectively. Usually, $\sigma_s^2 \ll \sigma_b^2$ because of the low signal level in comparison with the background. In most cases, one can assume that the value of ζ^2 is negligible in comparison with σ_b^2. However, the value of ζ^2 can be significant due to a subjective factor (e.g. the background level is erroneously calculated). For rough estimates, one can assume that $\sigma \cong \sigma_b \approx \sqrt{2 \cdot N_b}$. However, this expression is not accurate enough for detailed analysis. Besides, the value of N_b varies in time depending on the phase of solar activity cycle, local time, barometric pressure, state of the interplanetary medium, etc. Thus, when analysing NM data, it is necessary to take the averaged count-rate immediately before the event as a background and calculate the value of σ from the original count-rates. In addition, the trend in count-rate should be taken into account.

3 The dependence of the response of NM to solar neutrons on observational conditions

The response of a given NM to solar neutrons, N_n (counts), collected during the interval Δt can be written in the form (e.g. Debrunner *et al.*, 1989):

$$N_n = \int\limits_{t}^{t+\Delta t} \int\limits_{E_{th}}^{\infty} F_n(E,t') \cdot S_n(E) \cdot dE \cdot dt', \tag{3}$$

where F_n is the flux of solar neutrons at the Earth's orbit ($\mathrm{m^{-2}sec^{-1}MeV^{-1}}$), E is the neutron energy, $S_n(\mathrm{m}^2)$ is the sensitivity of the NM with respect to solar neutrons, E_{th} is the threshold energy ($\approx$ 50 MeV) for detection of solar neutrons by an NM.

The sensitivity of an NM to solar neutrons depends on the altitude of the NM location and the solar zenith angle. Using the following formula, one can determine the approximate value of the solar zenith angle, α, for a given time and day of observation:

$$\cos\alpha = \sin\varphi \cdot \sin\left(\frac{2\pi}{365} t_d\right) \cdot \sin\varepsilon + \cos\varphi \cdot \sqrt{1 - \sin^2\left(\frac{2\pi}{365} t_d\right)\sin^2\varepsilon} \cdot \cos\left(\pi \cdot \left(\frac{T}{12} + \frac{\lambda}{180} - 1\right)\right), \tag{4}$$

where φ and λ are the latitude and the longitude of the NM location, respectively, $\varepsilon = 23.5^\circ$ is the inclination of the equator relative to the ecliptic plane, t_d is the number of days after the spring equinox, T is the time UT in hours.

For a fixed flux of solar neutrons, the response of a given NM to solar neutrons is higher at a higher altitude of the NM and a smaller zenith angle. The northern hemisphere is more favourable for the neutron observations during the northern summer season, while the southern hemisphere is good for northern winter observations.

In Sect. 5 the results of calculations of the sensitivity of an NM with respect to solar neutrons will be discussed. These calculations have been carried out by means of Monte Carlo simulations of the cascading of vertically ($\alpha = 0^\circ$) incident solar neutrons into the Earth's atmosphere. Debrunner *et al.* (1990) presented the results of the sensitivity calculation for the value of α up to 42.5°. However, the statistical error of those calculations for $\alpha > 30^\circ$ is high. The problem of the angular dependence of the sensitivity is not yet clear. Therefore, an approximate empirical expression is usually used for the analysis of the response of the NM and for the comparison of responses of different NMs. The widely used expression is (e.g. Iucci *et al.*, 1984; Takahashi *et al.*, 1987)

$$N_n \propto \exp\left(\frac{-\kappa}{\lambda_n \cdot \cos\alpha}\right), \tag{5}$$

where $\lambda_n \approx 100\ \mathrm{g/cm^2}$ is the attenuation length of solar neutrons in the Earth's atmosphere.

Though observational data of the well-studied SNE of 3 June 1982, obtained from several NMs with values of α up to 32.5° (see Chupp *et al.*, 1987), were in a good accordance with Eq. (5), Debrunner *et al.* (1990) noted that their Monte Carlo simulations of S_n yielded less-pronounced angular dependence than that given by Eq. (5).

On 24 May 1990 the strongest SNE known so far (Shea *et al.*, 1991) was detected (see Table 1). The event was detected with high significance by three neutron monitors (Climax, Calgary and Mexico) (the signal had an amplitude greater than 20 standard deviations of the background). Responses of another four stations to solar neutrons from the same event were higher than 2σ and three monitors registered the event with low significance. The value of the solar zenith angle varied from 29° to 65° for different stations located at different altitudes from the sea level to 680 $\mathrm{g/cm^2}$ (see Table 1). Debrunner *et al.* (1993) and Kovaltsov *et al.* (1993) noted that the observations of this event disagreed with Eq. (5), which can only be used when the Sun is near zenith i.e. for $\alpha \approx 0$. For large values of the solar zenith angle, the NM's sensitivity function is underestimated.

Table 1. Responses of neutron monitors to the solar-neutron event of 24 May 1990 during the interval 2050–2055 UT

neutron monitor	type	$\cos\alpha$	κ, $\mathrm{g/cm^2}$	N_n, cnts/5 min	σ, cnts/5 min
Mexico	6 NM	0.8435	790	15214	404
Calgary	12 NM	0.8269	895	10357	322
Inuvik	18 NM	0.6712	1023	2539	366
Deep River	48 NM	0.6137	1020	3872	456
Durham	18 NM	0.5504	1029	508	261
Climax	12 IGY	0.8642	680	6896	192
Mt.Washington	12 IGY	0.5542	820	241	115
Newark	9 NM	0.6056	1030	619	206
Goose Bay	18 NM	0.4413	1027	269	375
Magadan	18 NM	0.4227	988	276	330

The underestimation is due to the fact that Eq. (5) takes into account secondary nucleons moving along the line of sight only. However, $\kappa \gg \lambda_n$ for all the monitors and the particles take part in several interactions before they reach an NM. Thus, the nucleons scattered into large angles play a significant role as well. Debrunner *et al.* (1993) showed that the observations of the 24 May 1990 SNE can be fitted by calculations of S_n (Debrunner *et al.*, 1990) within the limits of both observational and Monte Carlo statistical errors. Kovaltsov *et al.* (1993), on the basis of the data analysis, suggested a new approximate empirical expression which can be used for a wide range of the solar zenith angles α:

$$N_n \propto \cos^m \alpha \cdot \exp\left(\frac{-\kappa}{\lambda_n}\right). \qquad (6)$$

On the basis of experimental data of the 24 May 1990 SNE, we tested the hypothesis that the angular dependence of NM response to solar neutrons can be described using Eq. (6). This was done by varying the atmospheric attenuation length λ_n for neutrons and the exponent m of $\cos\alpha$ for the angular dependence. The value of R_n, the ratio of integral efficiencies of standard 6IGY and 6NM64 monitors with respect to solar neutrons, was used as an additional parameter. The following two criteria were chosen: (i) the χ^2 criterion at the significance level of 10% and (ii) the sign criterion (a model curve must lie between experimental points). For the study we made use of the data summarised in Table 1.

Figure 1 shows an area of possible values of the parameters in the λ_n-m plane. The thin curve limits the area for the value of $R_n = 0.07$, while the thick curve is a contour of the whole area of possible parameters $R_n = 0.05-0.09$. The point corresponds to the best fit values of the parameters: $\lambda_n = 104$ g/cm^2, $m = 4.0$, $R_n = 0.07$. Figure 1 shows that the area of possible values is quite narrow. The value of the attenuation length λ_n is found to be 100–110 g/cm^2. The value of m appeared to be 3.8–4.5 with the most probable value of 4.0. The ratio of the integral efficiencies R_n of the two types of standard monitors is 0.05–0.09 with the most probable value of 0.07.

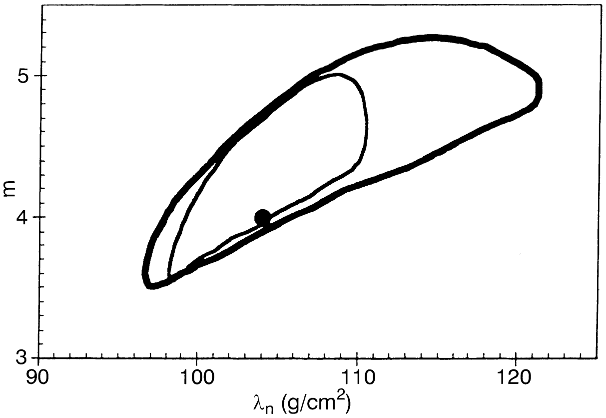

Fig. 1. Values of parameters m and λ_n of the empirical expression given by Eq. (6) for the neutron-monitor response to solar neutrons. The calculations were made for the 24 May 1990 solar-neutron event. The point corresponds to the best fit parameters

Thus, we believe that the functional form of the most optimal sensitivity function of an NM to solar neutrons can be described by Eq. (6) with $\lambda_n = 100$ g/cm^2, $m = 4.0$ and $R_n = 0.07$. These values will be used throughout this paper.

Recently, Smart *et al.* (1995) suggested an analogy that the atmospheric nucleon cascade can be considered as a needle-type beam of solar neutrons which converges by about 3° per λ_n of passed air mass. Thus, the "path" of the particles becomes shorter in comparison with the line-of-sight path. Their results are in a good agreement with Eq. (6). Developing their approach, we considered the cascade as consisting of inelastic processes, described by the exponential decay of the flux intensity, and elastic processes leading to scattering of the nucleons. We simulated the process of a sequenced scattering of solar neutrons in the Earth's atmosphere, by means of the Monte Carlo technique. We did not take into account processes leading to changes of the primary particle's energy. This is a goal of our further research. It appears as if the approximation Eq. (6) agreed rather well with the simulation results in the whole range of atmospheric depth and solar zenith angle values.

The observational data of the well-known SNE of 3 June 1982 are in good agreement with Eq. (6) as well. Note that preliminary analysis of recently presented NM records of the 6 June 1991 SNE (Muraki *et al.*, 1995) shows that the data agree with Eq. (6) while they contradict Eq. (5). Thus, at least for a practical use, Eq. (6) seems to be quite useful.

In the following the possibilities of the World Neutron Monitor Network to detect neutrons of solar-flare origin will be considered. The list of NMs, which are suitable for SNE registration, is summarised in Table 2. This table shows the geographical coordinates and altitudes of NMs, UT time of local noon T_{noon}, the signal-noise ratio N_n/σ (for an SNE on 3 June 1982 if the event had occurred at local noon. Observations of γ-radiation and neutrons of solar-flare origin carried out by both ground-based and space-borne detectors, during several recent cycles of solar activity, have shown that solar flares with such intensive high-energy neutron production as was observed on 3 June 1982, may be expected as frequently as several times per cycle (Mandzhavidze and Ramaty, 1992). Polar monitors are not included in Table 2 as they cannot reliably detect an SNE due to strong flux of GCR and large solar zenith angle in polar regions. Figure 2 shows the level at which the World Neutron Monitor Network could detect an event similar to the one on 3 June 1982 depending on the time of occurrence of the event. One axis corresponds to the date, the other to the time of day. Different shadings in Fig. 2 correspond to various values of the signal-noise ratio N_n/σ, where N_n is the response of an NM to solar neutrons and σ is the mean error of the NM count-rate. For Table 2 and Fig. 2, the value of σ was estimated as $\sqrt{2 \cdot N_b}$, where N_b was obtained from Eq. (1) for $\Delta t = 5$ min. The values of N_n for the NMs have been normalised with respect to the response of the Lomnický

Table 2. The list of neutron monitors ordered according to their ability to detect solar neutrons

Name	lat	long	P_c, GV	alt m	type	T_{noon} UT	N_n/σ max
Haleakala1	20.72	203.72	12.91	3030	18NM	22.419	37.7
Alma-AtaB	43.25	76.92	6.61	3340	18NM	6.872	32.7
Mt-Norikura	36.11	137.55	11.48	2770	12NM	2.830	23.8
Jungfraujoch1	46.55	7.98	4.61	3475	3NM	11.468	13.1
Mexico	19.33	260.82	8.60	2274	6NM	18.612	12.7
Lomnický Štit	49.20	20.22	3.98	2634	8NM	10.652	11.0
Tsumeb	−19.20	17.58	9.21	1240	18NM	10.828	10.7
Huancayo	−12.03	284.67	12.92	3400	12IGY	17.022	8.8
Jungfraujoch2	46.55	7.98	4.61	3475	18IGY	11.468	8.3
Haleakala2	20.72	203.72	12.91	3030	12IGY	22.419	8.0
Samarkand	39.60	66.9	7.50	830	24NM	7.540	7.3
Climax	39.37	253.82	2.99	3400	12IGY	19.079	6.6
Tokyo	35.75	139.72	11.63	20	28NM	2.685	5.6
Tashkent	41.33	69.62	7.50	565	18NM	7.359	5.4
Deep River	46.10	282.5	1.14	145	48NM	17.167	5.1
Tbilisi	41.72	44.8	6.73	510	18NM	9.013	4.9
Morioka	39.70	141.13	10.23	131	18NM	2.591	4.5
Calgary	51.08	245.87	1.08	1128	12NM	19.609	4.2
Darwin	−12.42	130.87	14.09	0	9NM	3.275	3.7
Alma-AtaA	43.25	76.92	6.61	775	6NM	6.872	3.5
Rome	41.90	12.52	6.32	60	17NM	11.165	3.5
Irkutsk	52.47	104.03	3.64	500	18NM	5.065	3.2
Hermanus	−34.42	19.22	4.58	26	12NM	10.719	3.1
Brisbane	−27.50	153.01	6.99	2	9NM	1.799	3.1
Durham	43.10	289.17	1.58	3	18NM	16.722	3.0
Mt-Wellington	−42.92	147.23	1.80	725	6NM	2.185	3.0
Kiev	50.72	30.30	3.57	120	18NM	9.980	2.8
Potchefstroom	−26.68	27.1	7.00	1351	15IGY	10.193	2.6
Kerguelen	−49.35	70.27	1.14	33	18NM	7.315	2.6
Mt-Washington	44.30	288.7	1.46	1909	12IGY	16.753	2.4
Newark	39.68	284.25	2.09	50	9NM	17.050	2.4
Sverdlovsk	56.73	61.07	2.23	300	18NM	7.929	2.3
Moscow	55.47	37.32	2.43	200	18NM	9.512	2.3
Goose Bay	53.27	299.6	0.64	46	18NM	16.027	2.2
Kiel	54.73	10.13	2.36	54	18NM	11.325	2.2
Alma-AtaC	43.25	76.92	6.61	1650	12IGY	6.872	2.2
Hobart	−42.90	147.33	1.84	15	9NM	2.178	2.2
Fukushima	37.75	140.48	10.61	66	4NM	2.635	2.1
Dourbes	50.10	4.6	3.34	225	9NM	11.693	2.1
Magadan	60.12	151.02	2.09	220	18NM	1.932	1.8
Apatity	67.55	33.33	0.57	182	18NM	9.778	1.2
Mirny	−66.55	93.02	0.03	38	18NM	5.799	1.1
Terre-Adelie	−66.55	140.02	0.02	35	18NM	2.665	1.1
Oulu	65.02	25.5	0.78	15	9NM	10.300	1.0
Inuvik	68.35	226.28	0.17	21	18NM	20.915	1.0
TixiBay	71.58	128.92	0.48	0	18NM	3.405	0.8
Mawson	−67.60	62.88	0.20	30	6NM	7.808	0.6

Štit (8NM64) to solar neutrons during 11:45–11:50 UT of 3 June 1982. Note that though the values of σ and N_n are approximate estimates, they can be used to study the general properties of the network. "Maps" *a* and *b* of Fig. 2 are plotted according to Eqs. (5) and (6), respectively. The value of N_n/σ corresponds to the most sensitive monitor, at the time of the SNE. One can see that the sensitivity of the world network to solar neutrons is much higher than earlier expected. The network can be used for continuous routine observations of SNEs, which is an advantage in comparison with space-borne experiments. The network can detect such strong events as the one on 3 June 1982 at a level 3σ or better, during 93% of observation time, events three-times weaker 54%, and events weaker by an order of magnitude for 9% of the observation time. The most sensitive to solar neutrons are the high-altitude monitors located at low and middle latitudes: Haleakala, Alma-Ata, Mt. Norikura, Jungfraujoch, Mexico, Lomnický Štit and Tsumeb (see Table 2). The network has a "dead time" with respect to solar neutrons (i.e. the network cannot detect even rather strong SNE) during morning hours, 04–08 UT, in winter time ("white area" in Fig. 2b). The "dead time" is caused by the natural absence of large mountain detectors in the region of Indian Ocean and Australia.

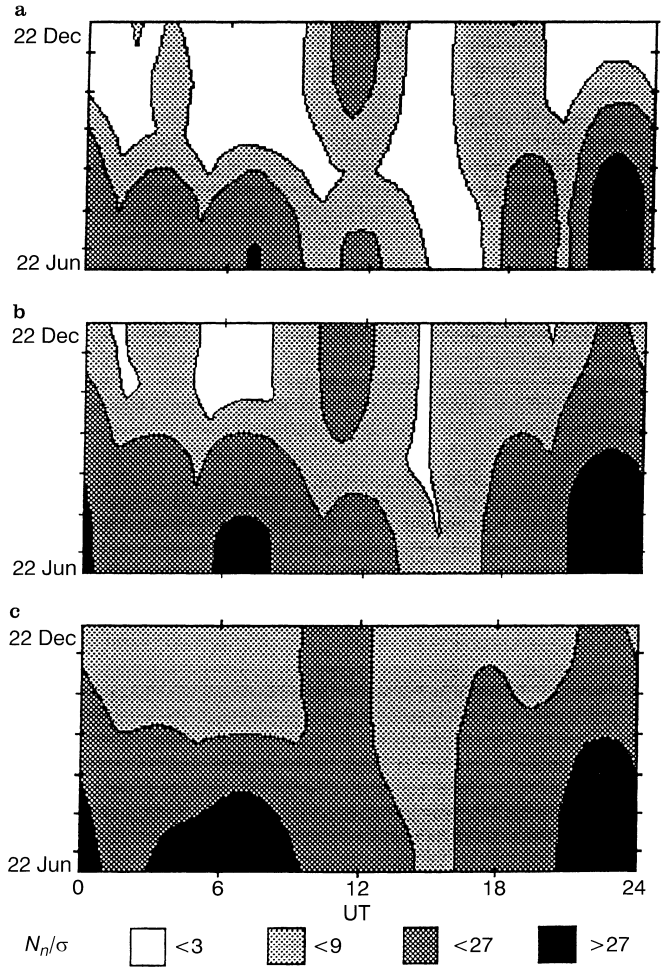

Fig. 2a-c. The sensitivity of the World Neutron Monitor Network to an intense solar-neutron event comparable to that of 3 June 1982 as a function of time of occurrence of the event. The shadowing corresponds to the significance of the detection of the event, in terms of N_n/σ. **a** The network sensitivity according to Eq. (5); **b** The network sensitivity according to Eq. (6); **c** The network sensitivity when the weighted summation of responses is applied

4 Weighted summation of NM responses

Assuming that responses of several NMs on the dayside of the globe are caused by a single SNE, one can use the information of the SNE not only from the NM with the largest response but from all the responding stations. The combined processing of different NM responses can be carried out using the techniques applied to a series of data with different values of accuracy (e.g. Hudson, 1964).

Monitors detect secondary nucleon flux initiated by solar neutrons in the Earth's atmosphere. The value of the flux depends on altitude and solar zenith angle of the observer [see Eq. (6)]. In order to consider responses of different NMs which have detected the event as independent measurements of the same flux of solar neutrons, one should normalise them to some standard conditions. Efimov *et al.* (1993) have suggested a 6NM64 monitor located at an altitude of $\kappa_{sc} = 660$ g/cm^2 as a standard instrument and standard observational conditions (this altitude corresponds to most mountain stations, Jungfraujoch, Alma-Ata, etc.) when the Sun is in the zenith, $\alpha_{sc} = 0°$.

Let the value of N_{ni} counts mean the response of the i^{th} NM to solar neutrons [see Eq. (5)]. This monitor is assumed to be located at an altitude corresponding to κ_i (g/cm^2) with a viewing of the Sun at the zenith angle α_i. The signal-noise ratio for this NM is N_{ni}/σ_i , where σ_i is the mean error of the background intensity. According to Eq. (6), the corresponding response X_i, for standard observational conditions should be:

$$X_i = N_{ni} \cdot r_{ni} \cdot \exp\left(\frac{\kappa_i - \kappa_{sc}}{100\mathrm{g/cm}^2}\right) \cdot \cos^{-4}\alpha_i, \tag{7}$$

where $r_{ni} = n_i/6$ for NM64-type or $r_{ni} = R_n \cdot n_i/6$ for IGY-type monitor with n_i counters. One can see that the reduction of the response to the standard conditions is simply a scaling of the signal.

In order to obtain the weighted response of the NM network to an SNE one should make use of weight factors which account for the reliability of every separate measurement. As the weight of the i^{th} measurement, the value $p_i = 1/\sigma_i^{*2}$ is used, where σ_i^* is the corresponding mean error of the value X_i. As long as the signal-noise ratio is constant at the scaling of the signal, one can obtain $\sigma_i^* = \sigma_i \cdot (X_i/N_{ni})$.

For the standard conditions, the weighted response of all the considered monitors to the SNE can be written as:

$$\xi = \frac{1}{p} \cdot \sum_i p_i X_i, \tag{8}$$

where $p = \sum p_i$ is the weight of the weighted response. The expected mean error of ξ, before the equalisation, is

$$\sigma_\xi = 1/\sqrt{p}. \tag{9}$$

On the other hand, one can calculate the actual mean error of ξ, after the equalisation, as

$$\sigma_\xi^* = \sqrt{\frac{1}{(n-1)p} \cdot \sum_{i=1}^{n} p_i (X_i - \xi)^2}. \tag{10}$$

In a general case, $\sigma_\xi^* \neq \sigma_\xi$. They are random values as they depend on measurement errors of separate monitors which are random. If those measurements did not contain a systematic error, the expected values of σ_ξ^* and σ_ξ would be equal. In the present case, the systematic errors could be introduced through several sources such as (a) the response of NM not to solar neutrons but to protons, (b) the uncertainty of the reduction Eq. (7) and (c) instrumental systematic errors. If $\sigma_\xi^* < \sigma_\xi$, the origin of the difference is random, and one can take the value of

$$\sigma_\xi^f = \left(\sigma_\xi^* + \sigma_\xi\right)/2 \tag{11}$$

as the final estimate of the mean error of the value of ξ. On the other hand, if $\sigma_\xi^* > \sigma_\xi$, one should calculate the value of a factor k:

$$k = \frac{\sigma_\xi^{*2} - \sigma_\xi^2}{\sigma_\xi^2} \cdot \sqrt{\frac{n-1}{2}}. \tag{12}$$

When $k < 2$, then, most likely, the difference between σ_ξ^* and σ_ξ is of random origin, and one can write the final estimate of the mean error of ξ as

$$\sigma_\xi^f = \sigma_\xi^*. \tag{13}$$

For $k > 2$, a systematic error exists in the series X_i. The factor k allows a verification of the accuracy of Eq. (6) as well as of the time of onset of a GLE in the case of the GLE following the SNE.

Thus, the weighted responses of different NMs with respect to an NM under standard observational conditions (as defined earlier) can be presented in the form:

$$N_{SC} = \xi \pm \sigma_\xi^f, \tag{14}$$

where ξ is determined by Eq. (8) and σ_ξ^f can be calculated from Eqs. (11) or (13).

In the following, the weighted summation of NM responses is applied to the event of 3 June 1982 which was detected by six neutron monitors: Jungfraujoch, Lomnický Štit, Rome, Kiel (Chupp *et al.*, 1987), Tsumeb (Stoker, 1987) and Alma-Ata (Zusmanovich and Shwartsman, 1987). The monitor most sensitive to solar neutrons at the flare time was the high-mountain monitor Lomnický Štit. It recorded the SNE at the maximum level of $N_n/\sigma = 7.3$ during the interval 11:45–11:50 UT. Figure 3a shows the time-profiles of count-rates for the monitors. The count-rate is normalised to that for standard observational conditions. The time-profile of weighted response for the six monitors is shown in Fig. 3b. The values of the weighted response ξ, reduced to the standard conditions, the mean error of ξ, σ_ξ^f, signal-noise ratio ξ/σ_ξ^f for this event are listed in Table 3. For the maximum of the event the value of the signal-noise ratio for the weighted response is 12.1, which is significantly higher than that for any separate monitor. Thus, the summation of responses offers an improvement in the detection efficiency for solar neutrons. Note that in the case considered, the value of the k factor was < 2, demonstrating that the difference in the responses of separate NMs was of random origin. The advantages of the method become even more obvious if, for the event, the responses of the most sensitive monitors, Lomnický Štit and Jungfraujoch were not taken into account. The individual responses of the other four NMs did not exceed the level of 2.5 σ. This value is too low for a reliable detection of the SNE. Fig. 3c shows the weighted response for the four monitors, excluding Lomnický Štit and Jungfraujoch.

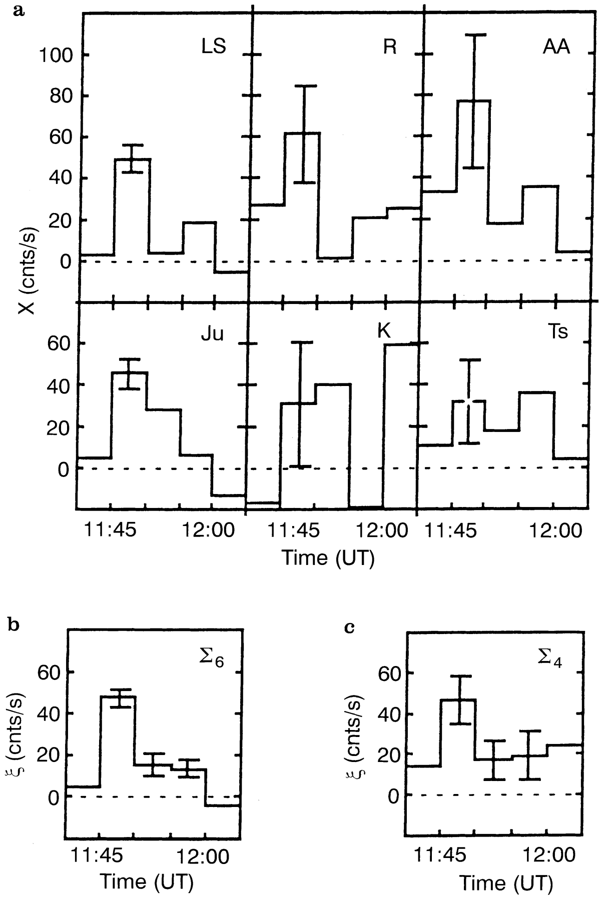

Fig. 3. a Responses of neutron monitors for the solar-neutron event on 3 June 1982 reduced to the standard observational conditions (see text): LS - Lomnický Štit; R - Rome; AA - Alma-Ata; Ju - Jungfraujoch; K - Kiel; Ts - Tsumeb; **b** the weighted summed response $\sum_6$ of the six NMs; **c** the weighted summed response $\sum_4$ of four NMs (R, AA, K, Ts)

The signal-noise ratio for the weighted response is 5.1 for the 11:45–11:50 UT interval, and the SNE can be detected with a high significance.

The sensitivity of the World Neutron Monitor Network to solar neutrons, when the responses of separate NMs are weightedly summed, is shown in Fig. 2c. One can see that within the entire year the existing network can detect, with a significance of $\geq 3\sigma$, an SNE as intense as that of 3 June, 1982. Events three times weaker can be reliably detected during 63% of the total observational time, and events ten times weaker during 15% of the time (compare with Fig. 2b). Thus, the use of weighted summation of NM responses significantly improves the efficiency of the network to detect weak SNEs.

Table 3. The weighted response (ξ) of the World Neutron Monitor Network (counts/s) under the standard observational conditions to the solar neutron event of 3 June 1982; σ_ξ^f = the mean error of ξ

	Time, UT				
	11:40–11:45	11:45–11:50	11:50–11:55	11:55–12:00	12:00–12:05
ξ	5.1	47.3	15.1	13.4	−4.5
σ_ξ^f	3.9	3.9	5.4	4.4	6.2
ξ/σ_ξ^f	1.3	12.1	2.8	3.05	−0.7

5 Test of the NM sensitivity to solar neutrons

In order to reconstruct the characteristics of the neutron injection from the Sun one should know the sensitivity of a monitor to solar neutrons as a function of their energy. There exist several calculations of the sensitivity of NM for solar neutrons, S_n, (Debrunner *et al.*, 1983, 1989, 1990; Chupp *et al.*, 1987; Efimov and Terekhov, 1988; Gueglenko *et al.*, 1990a; Shibata 1994). The results of the calculations differ significantly from each other. For instance, Fig. 4 shows the results of calculations of monitor sensitivity for the actual observational conditions of the 3 June 1982 SNE carried out by Debrunner *et al.* (1983, 1989, 1990), Chupp *et al.*, (1987) and Shibata (1994) for Jungfraujoch (18IGY) and Lomnický Štit (8NM64) monitors, and Efimov and Terekhov for Lomnický Štit NM (Efimov and Terekhov, 1988; Gueglenko *et al.*, 1990a). Hereafter, we denote the corresponding sensitivities as IGY-D and IGY-Sh as well as NM64-D, NM64-Sh and NM64-E, respectively. It is seen from Fig. 4 that in the energy range below 300 MeV there is great difference between the normalised values as well as between shapes of the sensitivity S_n (*e.g.* Shibata, 1994).

It is well known that the integral efficiency of the IGY monitor for solar neutrons is an order of magnitude lower than that of the NM64 monitor (Hatton, 1971). Thus, the ratio of these efficiencies can serve as a first rough criterion for testing the sensitivities. The sensitivity of the NM64-D is much lower than the sensitivities of both NM64-Sh and NM64-E, and also lower than the sensitivity for the IGY-D. On the other hand, the ratio between the NM64-E and the IGY-D sensitivities is reasonable and in accordance with the ratio R_n of integral efficiencies of the 6IGY and 6NM64 monitors, under the same observational conditions, for solar neutrons, observed on 24 May 1990 (see Sect. 3). Taking into account that the sensitivities given by Debrunner *et al.* (IGY-D and NM64-D) were based on the same atmospheric nucleon cascade simulation, we believe that the value of the integral efficiency of NM64-(Debrunner *et al.*, 1989, 1990) type monitor was underestimated by a factor of ≈ 20. Thus, we exclude the NM64- D sensitivity from further consideration. The IGY-D sensitivity seems to be correct. Both IGY-Sh and NM64-Sh sensitivities are in accordance with each other, although they are 4–6 times smaller than those by other groups (IGY-D and NM64-E). Thus, a need for more reliable tests for comparison of NM sensitivities is apparent. A solar flare, for which information about neutron production is obtained not only from NMs, but also from the detection of direct solar neutrons, neutron-decay protons, and γ-emission aboard satellites, can serve as such a test.

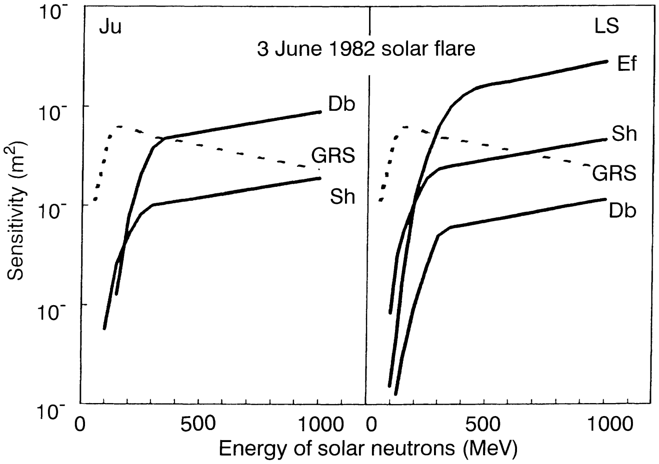

Fig. 4. The sensitivities of Jungfraujoch 18 IGY (*left plot*) and Lomnický Štit 8NM64 (*right plot*) neutron monitors to solar neutrons for the 3 June 1982 solar-neutron event. The sensitivities are: Db - IGY-D and NM64-D; Sh - IGY-Sh and NM64-Sh; Ef - NM64-E. The sensitivity of the GRS/SMM detector to neutrons is indicated with a *dotted line*

The SNE of 3 June 1982 was selected for this test. Neutrons were reliably detected by GRS aboard the SMM satellite, Lomnický Štit (8NM64 at 2632 m altitude, solar zenith angle 29°) and Jungfraujoch (18IGY, 3554 m, 24.5°) neutron monitors (Chupp *et al.*, 1987). Protons from neutron decays in the interplanetary space were detected as well (Evenson *et al.*, 1983). The flare has also been studied as a source of γ-ray emission (Ramaty and Murphy, 1987; Gueglenko *et al.*, 1990b; Mandzhavidze and Ramaty, 1992). The observed ratios between the integral (over the entire SNE) responses (counts) of NMs and GRS/SMM were $R_{Ju} = 0.36 \pm 0.06$ for Jungfraujoch/GRS and $R_{LS} = 0.61 \pm 0.09$ for Lomnický Štit/GRS. The GRS/SMM detector is sensitive to solar neutrons (Chupp *et al.*, 1987) of lower energy than the neutrons observed by monitors (see Fig. 4). Therefore, the values of R_{Ju} and R_{LS} depend on the steepness of the solar-neutron spectrum. Based on this fact and using the IGY-D sensitivity, Chupp *et al.* (1987) calculated for the event on 3 June 1982 the ratio R_{Ju} , between the integral count rates of the GRS/SMM and the Jungfraujoch IGY monitor, and reconstructed the spectrum of injected solar neutrons. In this paper a similar approach was applied.

Following the approach of Chupp *et al.* (1987), the calculations of the ratios were made using a power-law spectrum $f(E) \propto E^{-G}$ for the injected neutrons with cut-off at $E_{cut} = 2$ GeV and varying values of the spectral index, G. Developing their approach, we consider both R_{Ju} and R_{LS}, thus treating the case in two dimensions. Figure 5 shows the calculated values of R_{Ju} and R_{LS} as well as observed values of R_{Ju} and R_{LS} with $\pm\sigma$ and $\pm 2\sigma$ uncertainty ellipses. The monitor sensitivities IGY-D (Fig. 5a) and IGY-Sh (Fig. 5b) were chosen for the Jungfraujoch monitor and NM64-E (Fig. 5a) and NM64-Sh (Fig. 5b) for the Lomnický Štit monitor. It is seen from the figure that IGY-D and NM64-E sensitivities yield the values 2.5–2.7 for the spectral index G. This is in good agreement with the results obtained earlier by Chupp *et al.* (1987) using only the Jungfraujoch NM data. The spectrum of the injected neutrons must be much harder ($G = 1.3$–1.5) if the sensitivities IGY-Sh and NM64-Sh are used. Neither of the calculated curves crosses the $\pm\sigma$ area while both lines cross the $\pm 2\sigma$ area. This could result from either a

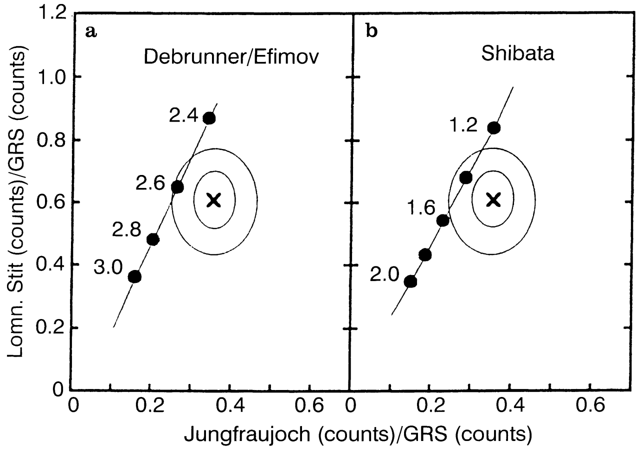

Fig. 5a, b. The ratio of the responses of neutron monitors to the response of the GRS instrument onboard the SMM spacecraft for the 3 June 1982 solar flare. The observed values are shown as *crosses* with 1σ and 2σ uncertainty *ellipses*. Lines correspond to calculated values of the ratio according to the IGY-D/NM64-E and IGY-Sh/NM64-Sh sensitivities (**a** and **b** plots, respectively). The figures correspond to values of the G index of a power-law spectrum of solar neutrons

statistical artefact or a systematic error. The fact that a and b of Fig. 5 are similar speaks in favour of a systematic error. For instance, such an effect may arise if the ratio of the integral efficiencies of the two monitor types, R_n, is overestimated by 20–30%. Shibata (1994) emphasised the importance of detailed knowledge of the sensitivity at a neutron energy < 300 MeV. However, even a considerable change in the shape of the function in this range could result in only slight changes of the spectral index G. The large difference in the values of G mentioned is mainly due to different normalisations of the sensitivity $S_n(E)$ by different groups, but not due to different shapes of the sensitivities in the energy range below 300 MeV.

Figure 6 shows the calculated neutron spectra for the 3 June 1982 SNE using the most probable parameters for the neutron injection according to sensitivities given by IGY-D/NM64-E and IGY-Sh/NM64-Sh. Also plotted are the characteristics of neutrons injected from the Sun on 3 June 1982 as they were associated with γ-ray emission and proton fluxes from neutron decay of the same flare (Evenson *et al.*, 1983; Ramaty and Murphy, 1987; Mandzhavidze and Ramaty, 1992). Also shown is neutron injection from the Sun corresponding to the observed flux of neutron-decay protons detected by ISEE-3 as well as neutrons corresponding to the observations of γ-emission in the 2.2-MeV-neutron capture line $n(p,d)\gamma$ and γ-emission from decay of high-energy π^0. Since pions and neutrons are produced simultaneously in solar flares, the generation rate of π^0-decay γ-rays (> 10 MeV) is proportional to the generation rate of neutrons (> 300 MeV). Estimates of the neutron spectrum were made using modern models of the 3 June 1982 flare (Gueglenko *et al.*, 1990a; Mandzhavidze and Ramaty, 1992).

One can see from Fig. 6 that the injected neutron spectra obtained in the case of IGY-D/NM64-E sensitivities are in a good agreement with other observations.

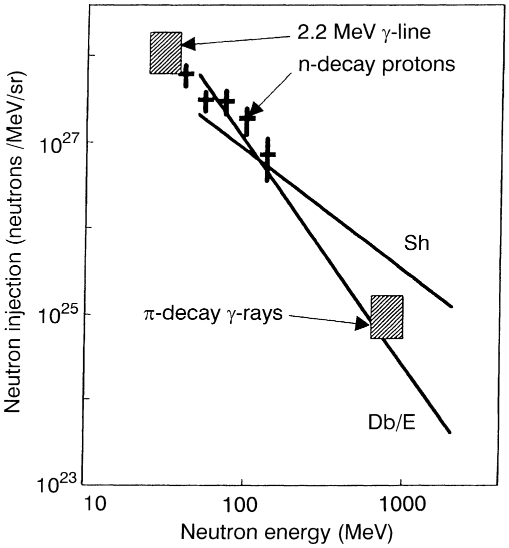

Fig. 6. Spectra of newly injected solar neutrons for the 3 June 1982 solar flare obtained using the IGY-D/ NM64-E (Db/ E) and IGY-Sh/ NM64-Sh (Sh) sensitivities in a comparison with neutron fluxes corresponding to observations of neutron-decay protons together with 2.2-MeV γ-line emission and pion decay γ-emission

The total number of neutrons with energy above 300 MeV injected from the Sun towards the Earth, as estimated from observations of π-decay γ-rays, was less than $2.5 \times 10^{28}\mathrm{sr}^{-1}$ for the flare. IGY-Sh/NM64-Sh sensitivities yield too high a flux of injected neutrons and too hard an energy spectrum. Based on observational data of the 2.2-MeV γ-line and neutron-decay protons, a steepening of this spectrum is expected below 100 MeV, which contradicts the established interpretation of the flare on 3 June 1982.

Recently, based on Climax (12IGY) NM data as well as on other observations of the flare emission, a reconstruction was made of the characteristics of solar-neutron injection from the Sun for the flare of 24 May 1990 (Kocharov *et al.*, 1994; Kovaltsov *et al.*, 1995a, b). The IGY-D sensitivity for the monitor was used for the reconstruction of the neutron spectrum. The flux of neutron-decay protons near the Earth was calculated and compared with high-energy proton observations by the GOES satellite (Kocharov *et al.*, 1995). The calculated results showed a reasonable agreement with the precursor recorded by GOES. If the IGY-Sh sensitivity were used, the calculated flux of neutron-decay protons would be several times higher than the one observed.

Thus, we may conclude that both the IGY-Sh and NM64-Sh sensitivity functions of an NM to solar neutrons are most likely underestimated. The IGY-D and NM64-E sensitivities are acceptable. Note that this analysis refers mainly to the test of integral normalisations of calculations of the sensitivity of an NM with respect to solar neutrons carried out by different groups. The difference in the shape of sensitivity in the range of neutron energy below 300 MeV is not crucial because, as will be shown in Sect. 6, the main contribution to the NM response, for not a very steep neutron spectrum, is due to neutrons with energy above 300 MeV. Though the shape of S_n for high neutron energies as presented by different groups is almost the same and we have tested the integral normalisation, the question of the shape of S_n in the range below 300 MeV seems still to be open. More detailed simulations of the atmospheric nucleon cascade and NM sensitivity for various angles of solar neutrons are necessary for further research of SNEs by means of the World Neutron Monitor Network.

6 Deduction of the number of solar neutrons from NM response

To study processes in the area of neutron production during a solar flare, it is very useful to determine both spectral and temporal characteristics of the injection of high-energy neutrons from the Sun. Unfortunately, an NM measures an integral flux of particles in cascades, initiated by different neutrons, which are mixed in the atmosphere, and a separation of the responses becomes impossible. Therefore, when analysing the response of an NM to solar neutrons one has to make some *a priori* assumptions on the spectrum of neutrons and temporal behaviour of their injection. Assumptions are commonly made based on observations of other types of flare-associated high-energy radiation. A comparison of the calculated response of an NM with the actual response allows one to obtain possible values of the parameters of an *a priori* assumption model of the neutron injection. For instance, such an approach has been used by Chupp *et al.* (1987) for the analysis of the 3 June 1982 SNE as well as by Debrunner *et al.* (1993) and Kocharov *et al.* (1994) for the analysis of the 24 May 1990 SNE. However, this approach can be applied only for strong neutron events for which the time-profile of the NM response can be obtained. For a weaker SNE only the response of an NM integrated over the entire event can be obtained. This time-integrated response is determined by the following expression:

$$Q_n = \frac{1}{R_a^2}\int_{E_{th}}^{\infty} f(E)\cdot S_n(E)\cdot \exp\left(-\frac{R_a}{\gamma\tau_n v}\right)\cdot dE, \qquad (15)$$

where $f(E)(\mathrm{sr}^{-1}\mathrm{MeV}^{-1})$, is the spectrum of neutrons injected from the Sun towards the Earth, integrated over the entire injection time. The exponent describes neutron decay in the interplanetary medium. τ_n is neutron decay time in intrinsic frame of reference. S_n and E_{th} are the sensitivity and the threshold energy of neutron detection of a NM with respect to solar neutrons. E, γ and v are energy, Lorentz-factor and velocity of a neutron, respectively. $R_a = 1$ AU. One can easily obtain Eq. (15) when e.g. integrating Eq. (4) of Debrunner *et al.* (1993) over the injection time.

The question may arise, What information about the flare can be obtained from this time-integrated response of NM? Since an NM measures an integral flux it seems natural to determine from the detected value of Q_n the total number of neutrons with energy above E_{norm} injected from the Sun towards the Earth, which is:

$$A_n(>E_{norm}) = \int_{E_{norm}}^{\infty} f(E)dE \text{ , sr}^{-1}. \qquad (16)$$

In a general case, in order to estimate the value of A_n on the basis of detected Q_n one should know the form and parameters of *in situ* neutron time-integrated spectrum, $f(E)$, which is unknown. In such a case, *a priori* assumptions have to be used. When such an approach is used the value of E_{norm} should not be chosen arbitrarily. The value of Q_n is fixed as a "detected" value, while the corresponding value of A_n depends on the choice of E_{norm} and the unknown spectral form of $f(E)$. The fact that $f(E)$ is unknown can be included as a systematic error of determination of A_n from Q_n. For an arbitrary value of E_{norm} this error is so high that the determination of A_n from Q_n without additional assumptions is impossible. Thus, the value of E_{norm} should be chosen so that the systematic error is minimised. The fact that such a value E^*_{norm} of E_{norm} exists means that the value of Q_n can be directly associated with the value of $A_n(> E^*_{norm})$ irrespectively of the shape of $f(E)$. Therefore, one can estimate with some accuracy the value of the total number of neutrons injected from the Sun without any *a priori* assumption of the shape of $f(E)$.

In our study we used for the energy spectrum of injected neutrons (see e.g. Chupp *et al.*, 1987) an exponential spectrum $f(E) \propto \exp(-E/E_o)$ with E_o as the characteristic energy of the spectrum as well as a power-law spectrum $f(E) \propto E^{-G}$ with cut-off at energy E_{cut}. We calculated the response Q_n, of a NM64-type NM integrated over the entire event, using the sensitivity $S_n(E)$ NM64-E according to Efimov and Terekhov (1988), for a fixed total number of injected neutrons. For illustration of the results of the calculations, an exponential spectrum of injected neutrons is chosen, though all the conclusions below are true for power-law spectra as well. Figure. 7 shows the calculated value of Q_n vs. E_o for various values of the normalisation energy, E_{norm}. One can see that for $E_{norm} \approx 300$ MeV the dependence

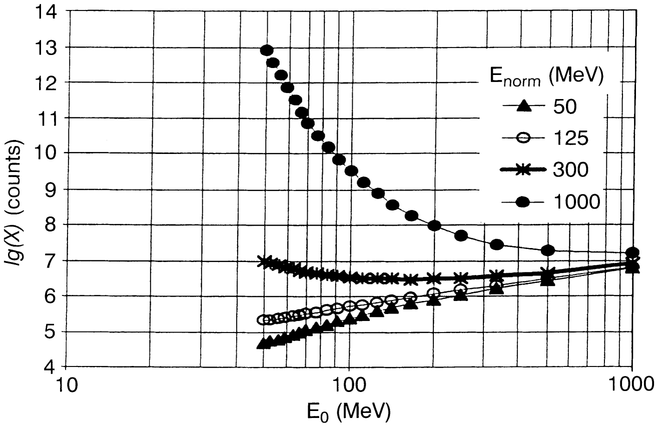

Fig. 7. The logarithmic response of a neutron monitor to solar neutrons for the standard observational conditions (see Sect. 4) as a function of the characteristic energy E_o of an exponential solar-neutron spectrum. The total number of neutrons with energy above E_{norm} injected from the Sun towards the Earth is fixed at 10^{30} neutrons/sr. Different curves correspond to different values of E_{norm}

of the response Q_n on the neutron spectrum $f(E)$ is weak. In other words, the total number of neutrons with energy above 300 MeV injected from the Sun towards the Earth can be deduced from the integrated response of a neutron monitor without knowledge of the shape of the neutron spectrum. The accuracy of deduction of the value of A_n from Q_n, although not high (within a factor of 3), is enough to be used in study of high-energy processes taking place in solar flares. Note that the content of this section concerns SNEs for which a complex analysis of γ-emission and direct neutron detection is impossible. Otherwise, records of NM count-rates during an SNE can serve as an additional information for a comparison with other data and to check the validity of the models.

Using a normalisation energy of 300 MeV the total number of high-energy solar neutrons injected from the Sun towards the Earth has been plotted against the atmospheric depth of NM location (Fig. 8). This figure shows (solid line) the number of neutrons injected from the Sun, $A_n(> 300\,\mathrm{MeV})\,\mathrm{sr}^{-1}$, per count (above the background) of a 6NM64 monitor located at the altitude of κ g/cm^2, at a sub-solar point (solar zenith angle $\alpha = 0°$), collected during the entire SNE. Dotted lines correspond to estimated uncertainties. For the time-integrated response Q_n of a certain NM located at the altitude of κ g/cm^2 with the solar zenith angle α, the corresponding total number of neutrons (> 300 MeV) injected from the Sun towards the Earth can be calculated, using Eq. (6), as

$$A_n(> 300\ \mathrm{MeV}) = Q_n \cdot y(\kappa) \cdot \cos^{-4}\alpha \cdot r_n\ ,\mathrm{sr}^{-1}, \qquad (17)$$

where $y(\kappa)$ should be found from the curve in Fig. 8, $r_n = n/6$ for NM64-type (or $r_n = R_n \cdot n/6$ for IGY-type) monitor with n counters. In the case of an SNE detected by several NMs, the weighted response ξ of the network should be used for calculation of $A_n(> 300\ \mathrm{MeV})$:

$$A_n(> 300\ \mathrm{MeV}) = \xi \cdot y(\kappa)\ ,\mathrm{sr}^{-1}. \qquad (17a)$$

In order to illustrate how the approach works, let us consider the well-known case of the 3 June 1982 event. The weighted response of the Neutron Monitor Network, reduced to the standard observational conditions (a 6NM64 monitor located at the altitude of $\kappa =$ 660 g/cm^2 at sub-solar point, $\alpha = 0°$) was $\xi = 24270$ counts above the background during the period 11:40–12:00 UT (see Table 3). According to Eq. (17a), the corresponding value of $A_n(> 300\,\mathrm{MeV})$ is $(4-10)\cdot 10^{27}\mathrm{sr}^{-1}$, which is in agreement with the value obtained by Chupp *et al.* (1987).

Thus, when using Fig. 8 and Eqs. (17), (17a), one can immediately estimate from the observed response of an NM to an SNE with an accuracy of a factor of 3, the total number of neutrons (> 300 MeV) injected from the Sun. Therefore, the approach can be recommended as a fast preliminary analysis of a strong SNE and for a regular study of a weaker SNE when additional information about injected neutrons cannot be obtained. This approach can also be applied to a solar flare for which only an upper limit of the NM response can be obtained from observations. From this upper limit response, the corresponding upper limit of the total number of injected neutrons can be estimated, which is also very important for solar-flare physics.

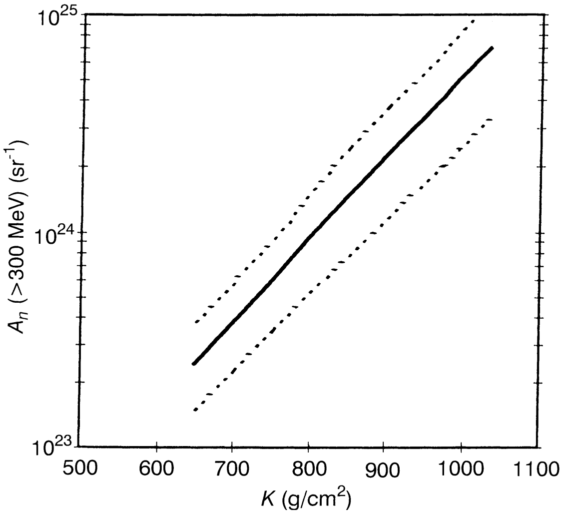

Fig. 8. The calculated number (*solid line*) of neutrons injected from the Sun towards the Earth per count of a 6NM64 monitor vs. the altitude of the NM station. The Sun is assumed to be in the zenith. *Dotted lines* correspond to estimated uncertainties of ± σ

7 Concluding remarks

It has been shown that the ground-based World Neutron Monitor Network is a suitable tool for research of high-energy solar-flare neutrons. The advantages of this network are its continuos operation as monitor of solar and galactic particles, its relatively low cost of operation and its long continuity of observations (over several solar cycles). One of its main disadvantages is the fact that an NM detects not the original solar and galactic nucleons, but nucleons of an atmospheric cascade initiated by the primaries. This may introduce some errors in the study of solar neutrons by means of neutron monitors. In order to avoid or, at least, to minimise these errors, a detailed numerical simulation of the atmospheric cascade process should be carried out. Even though the errors still exist, the records of NM responses to SNEs are of great value for solar physics.

Note that high-altitude equatorial monitors are best suited for the study of solar neutrons, while high-latitude and polar stations are more effectively used for the research of cosmic rays. Thus, both equatorial and polar NMs combined with space-borne instrumentation can provide important information on the processes of particle acceleration, propagation and interactions in solar flares.

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