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Spectrometer for neutron and gamma-ray detection at the distances less than 100 solar radii from the Sun

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Abstract. Solar neutrons with energies <5 MeV can't be detected in the near-Earth space due to the both its decay and decreasing of its fluxes with distance from the Sun. So solar neutron observations near the Sun compared with near-Earth ones allow studying acceleration of ions up to significantly smaller energies, what occurs considerably more often. Besides that near-Sun low energy neutron observations are important for search for non-flare ion acceleration on the Sun. For project InterHelioProbe we have proposed spectrometer of neutrons with energies 0.05-5 MeV. LiI(Eu) crystal 4*3 cm enriched in ^{6}Li , surrounded by a plastic scintillator 1-3 cm thick loaded with ^{10}B is used as a detector. Neutrons will undergo elastic scattering with the hydrogen in the plastic. A delayed coincidence within a window of 0.1 – 10 μs in either scintillator is a signature of a neutron, with the initial fast plastic signal pulse height being a direct measure of the incident neutron's energy. A fast charged particle will be vetoed as simultaneous signals in both scintillators. Gamma's with energies 0.03-10 MeV will be identified too as signals in LiI alone. Calculated effective area for normal neutron incidence is 0.3-5.6 cm^2. Estimated effective area for gamma detection is 3-12 cm^2. Mass of the instrument is <1.5 kg. Power of the detector is about 1.5 watt, needing telemetry – 40 b/s.

1 Introduction

Sun flare activity is characterized by electromagnetic emission in a wide range of wavelength from radio waves up to the gamma radiation, by coronal mass ejection, and by fluxes of energetic charged particles and neutrons. In the studying of all this complex of solar activity phenomena information about fluxes of gamma rays and neutrons is very significant so appearance of these fluxes is evidence of ion acceleration up to high enough energies. Information about spectra of solar neutrons and gamma-quanta allow to more correct determine spectra of accelerated ions. To obtain the most complete information, simultaneous observations of solar X-ray emission, gamma's and neutrons are necessary.

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2 Estimations

To estimate how changes registration condition of solar neutrons from the Earth orbit to the near-Sun vicinity we calculated solar neutron flux and spectra for the distance from the Sun equals to 214, 100, and 25 solar radii.

The neutron flux at the detector varies as $1/r^2\ P_S\ (E_n, r)$, where $P_S\ (E_n, r)$ is the probability of survival of a neutron of energy E_n at a distance r from the source. Basically, $P_S\ (E_n, r) = exp(-t(E_n)/\gamma\tau)$, where t is the transit time of a neutron of energy E_n to the detector, τ is the proper mean lifetime of the neutron (887 s), and $\gamma = [1 - (\mathrm{v}(E_n)/c)^2]^{-1/2}$ is the time dilation factor, with $\mathrm{v}(E_n)$ the velocity of a neutron with energy E_n. At the Earth's orbit $P_S\ (E_n, 1\mathrm{AU})$ is 0.3 for 100 MeV neutrons, 0.02 for 10 MeV neutrons, and 5×10^{-6} for 1 MeV neutrons. At 25 solar radii (R_S) the corresponding values for $P_S\ (E_n, 25\ R_S)$ are 0.9, 0.7, and 0.2 for neutrons with the energies 100 MeV, 10 MeV, and 1 MeV respectively. Thus there is a dramatic increase in the survival probability of the lower energy neutrons near the Sun as compared to those near the Earth (> 10^4 for 1 MeV neutrons). This fact immediately suggests that the observation near the Sun of these low energy neutrons, under quasi-steady or flaring conditions, would prove the presence of accelerated low energy ions. This, in turn, would lead directly to the determination of the energy input to the low solar atmosphere from these ions - an observation that cannot be made by any other means, since one must be near the Sun to observe low energy neutrons, a proof for low energy ions presence in the corona.

Figure 1 shows the dependence of the neutron flux on the neutron arrival time at distances from the Sun of 214 R_S, 100 R_S, and 25 R_S. In this case, the abscissa refers to the neutron arrival time delay at the spacecraft relative to photons (e.g. gamma rays) produced coincidently at the Sun. In Figure 2, we show relative flux of neutrons versus neutron energy at the same distances from the Sun and for neutron energy spectra at the source with original negative power law indices of 1.6, 2, and 3. These spectra depend, in turn, directly on the spectra of primary ions, which produce the neutrons. These figures are appropriate to the case of a flare in which the neutron production time is small compared to the neutron transit time to the detector (δ-function case). Again, the dramatic effect of distance on the relative neutron flux is evident. Of course, the neutron arrival time depends on both the neutron energy and the distance from the Sun where the neutrons are observed. For observations at 25 R_S, 100 MeV neutrons will arrive ~ 78 s after the first gamma rays and 1 MeV neutrons would arrive ~ 1200 s later, so in the δ-function case, the neutron's arrival time is a direct measure of its energy. In the case of continuous or quasi-continuous nuclear reactions at the Sun, neutrons of different energies can arrive at the same time.

3 **Method**

A major factor in the design of a detector capable of recording neutron and gamma ray spectra in the experiment on near-Sun orbit is its overall weight. The mass of neutron/gamma-ray spectrometers on Earth-orbiting satellites is often several hundred kg. For neutron detection we chose detector similar to that designed in our institute earlier (Shavrin et al., 1972). Estimated mass of the detector is not more, than 1.5 kg. The design also benefits from the heritage of the SONG detector that was flown aboard the CORONAS-I satellite (Balaz et al., 1994).

A LiI crystal enriched in ^{6}Li (96%), which has a high cross-section for thermal neutron capture (~ 945 b), is surrounded by a plastic scintillator loaded with ^{10}B which also has a high cross-section for thermal neutron capture (~ 3835 b). Both scintillators are viewed by a single photomultiplier tube, with plastic and LiI signals separated by pulse shape sensitive electronics. This is the standard "phoswich" technique. The scintillators have the following parameters: Plastic: ∅8 cm and 7 cm thick, LiI: ∅4 cm and 3 cm thick, distance between LiI and PMT is 1 cm. The PMT has dimensions ∅5.2*11 cm. A neutron with the energy 0.05-5 MeV will undergo elastic scattering with the hydrogen in the plastic, giving a fast (several ns) pulse with the neutron slowing to thermal energies, and can be captured by a ^{10}B nucleus in the plastic or by a ^{6}Li nucleus giving large energy releases from the exothermic (n,α) reactions. In particular, we have the reactions $^{10}B(n,\alpha)^7Li$ + 2.3 MeV or $^6Li(n,\alpha)^3H$ + 4.6 MeV. Since the neutron thermalization and capture time is long compared the initial plastic pulse, a delayed coincidence within a window of (0.1 – 10 μs) in either scintillator is a signature of a neutron, with the initial fast plastic signal pulse height

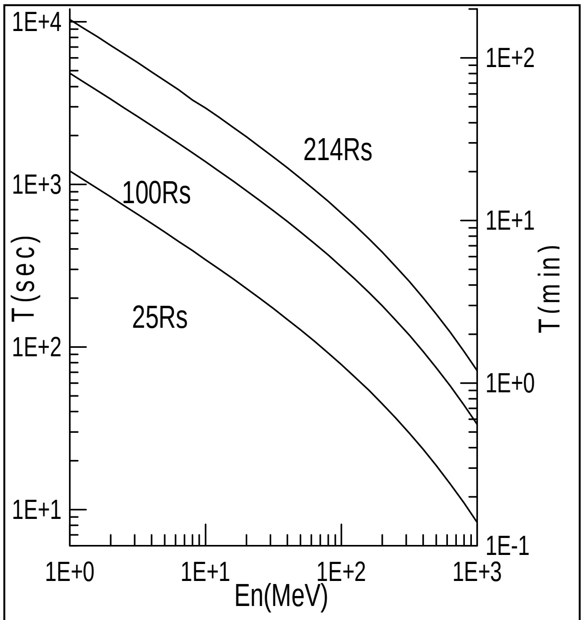

Fig. 1. Time delay of neutron relatively gamma-quantum arrival time vs. neutron energy at distances from the Sun of 214 R_s, 100 R_s and 25 R_s

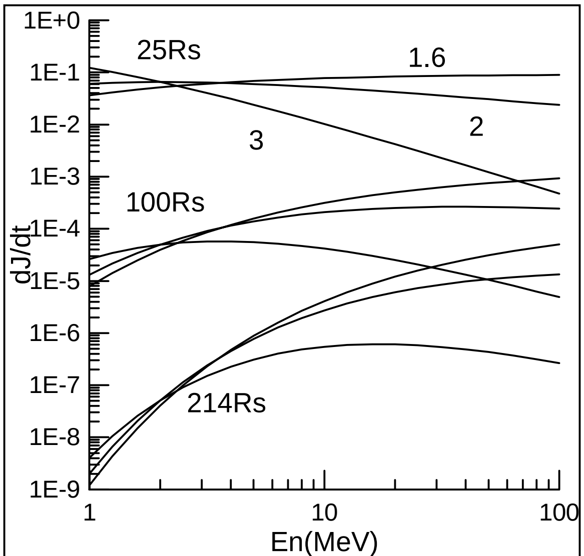

Fig. 2. Dependence of the relative neutron flux on neutron energy at distances from the Sun of 200 R_s, 100 R_s and 25 R_s for neutron energy spectra with negative power law indices of 1.6, 2 and 3.

being a direct measure of the incident neutron's energy. The endothermic reaction ^{6}Li(n,n′α)^{2}H – 1.5 MeV with cross-section 0.4 b and threshold energy of about 5 MeV permits a measurement of fast neutrons, which do not undergo elastic scattering in the plastic. Counting rates of single events with energy release of about 2.3 MeV in plastic or of about 4.6 MeV in LiI which are due mainly to the neutrons with the energies <0.5 MeV will be measured too. A fast charged particle will produce simultaneous signals in both scintillators and will be vetoed by the fast anticoincident signal. The detector also identifies gamma rays by the presence of a ^{6}Li signal without a corresponding simultaneous signal in the plastic scintillator. The energy resolution of ^{6}Li is ~ 12% at 662 keV. This is not as good as the standard of ~ 7% set by NaI, for example, but still capable of resolving gamma-ray lines in the spectrum. Thus the detector will be able to measure the incident x-ray and gamma ray spectrum over a nominal energy range of 30 keV to 10 MeV. Weight breakdown of the detector components is listed in Table 1. We will investigate ways to reduce the mass, for example by replacing the photomultiplier tube (140 g) with less massive photodiodes (~ 10 g). Power of the detector is about 1.5 watt, needing telemetry – 40 b/s.

Table 1. Detector component weight breakdown (g).

Plastic scintillator	330
LiI	150
PMT	140
Housing of PMT and combined scintillator	350
Inert materials	Integrated with spacecraft construction
Electronics with housing	500
Total	1470

New plastic scintillator loaded by natural mixture of isotopes of B for our instrument was created in Laboratory of Nuclear Physics of Joint Institute for Nuclear Research (Brudanin et al., 2000, Bogomolov et al., 2000). It was shown by Bogomolov et al (2000) that the scintillator compared with unloaded by B one up to the 5% mass fraction of B have very similar transparency and photoluminescence spectra and light output, decreased with the B mass fraction increasing. For the sample with mass fraction of B equals to 5% light output is 0.7 of unloaded one.

Monte-Carlo simulations of the neutron interactions with the detector were performed to determine the best geometry of the detector, optimum concentration of ^{10}B, and the best value of delay time of the scheme of delayed coincidences. Calculations were made for parallel beam of neutrons of fixed energies incident normally to the detector surface. Two variants of the detector geometry were used for simulations:

1. Plastic scintillator ∅70×70mm and LiI ∅50×30mm
2. Plastic scintillator ∅80×70mm and LiI ∅40×30mm

Calculated spectra of delay time of the interactions of neutrons with ^{6}Li and ^{10}B relatively to the moment of first elastic scattering on nucleus of hydrogen for energies 0.1 and 5.6 MeV are shown on Figure 3.

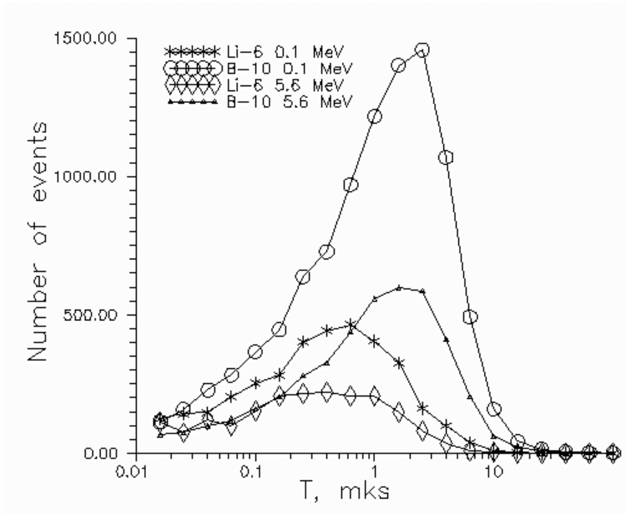

Fig.3. Spectra of the delay time of the neutron interaction with nuclei ^{6}Li and ^{10}B relatively to elastic scattering on nuclei of hydrogen.

Calculations were made for ^{10}B mass concentration 0.04 for variant 2. It is seen from the Figure, that ^{10}B event spectra have a distinct maximum at the times 1.5-3.0 μs. Forms of the spectra are weekly dependant on the energy in the whole range 0.1 – 5.6 MeV. Forms of the ^{6}Li event spectra is weekly dependant on the energy too, but its maxima are broader and are shifted at lower energies (0.2-1.0 μs). So, from Figure 3 we can see that time interval from 0.1 to 10.0 μs is quite suitable for delayed coincidence neutron detection.

On Figure 4 we show energy dependencies of calculated effective areas of our detector for neutron detection summarized for ^{6}Li and ^{10}B events for both variant 1 and 2 and for amounts of B of 0.01, 0.02, and 0.04. Variant 1 is marked as "7 cm" and variant 2 – as "8 cm". It is seen, that for the used amounts of B effective area is mainly dependent not on the B amount but on the detector geometry. Effective area for variant 2 is approximately two times as large as that of variant 1 while the mass of the detector for variant 2 is only 1.05 of that of variant 1 and its effective area for gamma-ray detection is about 0.7 of that of variant 1. As the most interesting for the near-Sun measurements of energetic neutral emission is neutron observations variant 2 is preferable one. Effective area for neutron detection in this variant varies from 5.6 cm^2 for 0.1 MeV to 0.26 cm^2 for 5.6 MeV. 24-27% of this effective area is due to ^{6}Li events and remaining part – to ^{10}B events. According to estimations gamma-ray detection effective area varies from 12 cm^2 for 0.03 MeV to 3 cm^2 for 10 MeV.

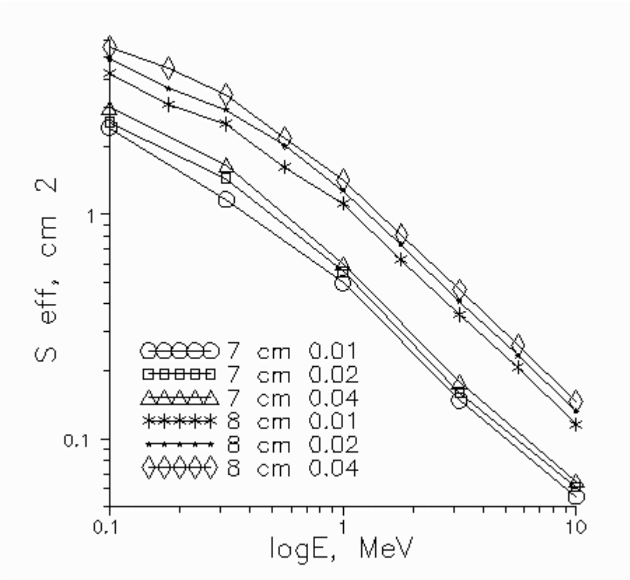

Fig.4. Dependence of the effective area of the detector on the neutron energy

4 Conclusions

Spectrometer with the mass not more than 1.5 kg for the neutrons with the energies 0.05-5 MeV and X- and gamma-quanta with the energies 0.03-10 MeV detection suitable for observations near the Sun is proposed for the project InterHelioProbe.. It allows studies of ion acceleration processes by simultaneous observations both undetectable near the Earth neutrons of small energies and of hard electromagnetic emission – X and gamma rays. Monte-Carlo simulation of the delayed coincidence mode of neutron detection by the instrument is performed. Response function and energy dependence of the effective area are calculated. Effective area for neutron detection varies from 5.6 cm^2 for 0.1 MeV to 0.26 cm^2 for 5.6 MeV.

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