

Measurement of High-Energy Solar Neutrons with SEDA-FIB onboard the ISS

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Abstract: A new type of solar neutron detector (SEDA-FIB) was launched on board the Space Shuttle Endeavor on July 16 2009, and began collecting data at the International Space Station (ISS) on August 25 2009. This paper summarizes four years of observations with the solar neutron detector SEDA-FIB (Space Environment Data Acquisition using the FIBer detector). The solar neutron detector FIB can determine both the energy and arrival direction of solar neutrons. In this paper, we first present the angular distribution of neutron induced protons obtained in Monte Carlo simulations. The results are compared with the experimental results. Then we provide the angular distribution of background neutrons during one full orbit of the ISS (90 minutes). Next, the angular distribution of neutrons during the flare onset time from 20:02 to 20:10 UT on March 7 2011 is presented. It is compared with the distribution when a solar flare is not occurring. Observed solar neutrons possibly originated from the M-class solar flares that occurred on March 7 (M3.7), June 7 (M2.5), September 24 (M3.0) (weak signal) and November 3 (X1.9) of 2011 and January 23 of 2012 (M8.7). This marked the first time that neutrons have been observed from M-class solar flares. A possible interpretation of the neutron production process will be also provided.

Keywords: solar neutrons, SEP, solar comic rays, proton acceleration.

1 Introduction

The first results from the solar neutron sensor, SEDA-FIB, onboard the International Space Station were presented at the previous cosmic ray conference in Beijing [?]. In this paper the current status of the analysis is reported.

The paper consists of the following: First we give the details of the detector and trigger logic. Then Monte Carlo results for the angular resolution of neutrons are presented and the findings are compared with experimental results. We present the angular distribution of background neutrons, which are formed by collision of galactic cosmic rays with the materials of the space station.

Next, we give the angular distribution of neutrons in relation to the solar direction during the flare onset time. The results indicate that solar neutrons were successfully detected. The events are discussed together with a possible production mechanism. In association with the M-class solar flares during March 2011 and January 2012, solar neutron events were also observed.

Recently, solar activity has once again increased. In the final part of this paper, new results of the analysis of these flares during April and May of 2013 may be given.

2 Details of the Detector

2.1 Composition of the sensor

The solar neutron detector SEDA-FIB is composed of scintillation bars, each with dimensions of 6 mm (width)×3 mm (height)×96 mm (length). Each layer in the detector consists of 16 bars, so each layer has dimensions of 96

mm×96 mm×3 mm (thickness). Such layers are stacked at right angles to each other to form the detector. A schematic view of the detector is shown in Figure 1.

The signals are read out by using two multi-anode photomultipliers (Hamamatsu R4140-20MOD) with 256 read-out channels. (Initially, we were concerned about discharge at the corner of the photomultipliers, but this has not had any serious effects on observations.) The detector records not only the coordinates of the track of the detected particle but also the energy deposited in each bar. With this information, we could distinguish neutron-induced protons from photon-induced electrons.

When neutron-induced protons stop in a scintillator bar, they deposit the bulk of their energy within in. From the Bragg peak, we can determine the direction of the incoming neutrons. An actual example of an event is presented in Figure 2. The signal threshold of the ADC channel is set above ~ 11 and the peak value for a minimum ionizing particle (MIP) is set at around ~ 22 . The value varies between channels. The red color in Figure 2 corresponds to a ADC channel value of 64(G-max) and the blue color corresponds to 11 (G-min). This means that an ADC channel value of 66 corresponds to six times the value of the MIP. The sensor has a cubic shape and its volume is approximately $1,000\text{cm}^3$. The six faces of the cubic detector are covered by six pieces of scintillator plate with size of $10\text{ cm} \times 10\text{ cm} \times 1\text{ cm}$ (thickness). These scintillator plates are used as an anti-counter to remove the effect of other charged particles on the results. They work very well and protons and electrons are rejected very efficiently. The signals due to neutron-induced protons are sent to the two photomultipli-

ers via 512 optical fibers, each 1 mm in diameter. The two photomultipliers are orientated in the X-Z and Y-Z planes of the sensor respectively. Here the X-direction is defined as the direction to the Earth's center and the Y-direction is opposite to the direction of motion of the ISS, which is perpendicular to the X-direction as the ISS is orbiting the Earth. Small holes (2×256 holes) run through the two scintillator plates to accommodate the optical fibers. Further details of the detector have been published elsewhere [?], [?],[?].

2.2 Trigger of signals

The trigger signals are produced by the dynode signals of each photomultiplier. When the sum of the dynode signals exceeds 35 MeV, a trigger signal is created and the amount of energy deposited in all the scintillator bars is recorded. When the trigger rate exceeds 16 counts/sec, only the coordinates of the tracks are recorded; however, this function actually works when the trigger rate exceeds about 2 counts/sec. If the count rate exceeds 64 counts/sec, only the deposited energy in each dynode is recorded. This may happen when the sensor passes through the South Atlantic Anomaly region or during a period of high neutron flux. The typical trigger rate over the Equator is 0.07 counts/sec, while over the North or South polar regions it is 0.4 counts/sec. The average trigger rate is about 0.22 counts/sec. The trigger rate sometimes exceeds over 20 counts/sec above the SAA region.

The correspondence between the sum of the ADC values and the dynode signal is quite good. The ADC signals are analyzed after removing the background pedestal value from each channel. The pedestal and the peak values for the MIPs of all 512 channels are estimated from the results of proton beam experiments at Riken, Japan and cosmic ray muon data before launching.

2.3 Pointing Ability of the Sensor to Determine the Direction of Incoming Neutrons

To distinguish solar neutrons from background radiation, the pointing ability of the sensor is very important. If observations of solar neutrons are made in the background free space between the Sun and the Earth, it is not necessary to take this into account; however, in our experiment on the ISS, the process becomes very important. We have estimated the power by both actual experiments and by MC calculations. The experiments were made in 1999 and 2000 using the RCNP neutron beam at Osaka University [?]. In this paper we present the angular distribution as predicted by the MC simulation based on the Geant-4 program. The results are compared with the experimental results.

Figure 3 shows MC results for the angular distribution of protons induced by vertically incident neutrons from above the sensor with an energy of 80 MeV. The black circles correspond to events induced by neutrons inside the cubic sensor (the dimensions of which are $10 \text{ cm} \times 10 \text{ cm} \times 10 \text{ cm}$) without using the anti-counter, while the white squares represent the signals recorded by the sensor with the use of the anti-counter, i.e., neutron-induced protons are involved inside the sensor. To produce these results, one million neutron events were generated. The simulation was made for different incident energies, from 60 to 200 MeV; however, the general character of the results did not change with incident energy.

The MC results were next compared with the experimental results. The experimental results shown in Figure 4 are

for an incident energy of $E_n=80\text{-}100$ MeV. Through comparison of Figure 3 and 4, it is apparent that the MC results reproduce the experimental results quite well.

The MC simulation predicted peaks of scattered protons at around 20 degrees from the direction of the incident neutrons. The distribution spreads from 0 to 50 degrees. This implies that solar neutrons and background neutrons can be distinguished if we only consider neutron induced protons within a cone of 30 degrees around the solar direction. This reduces the effect of background neutrons by approximately 16 times, if we assume the background neutrons come equally from all directions.

The detection efficiency for neutrons with deposited energy over of 35 MeV is predicted by the MC calculation to be 0.02 at 60 MeV, 0.023 at 80 MeV, 0.02 at 100 MeV, and 0.015 at 140 MeV respectively. The experimental results give values of 0.02, 0.018, 0.014 and 0.003 respectively. Thus, there is good agreement between the MC numerical and experimental results.

3 Angular Distribution of Background Neutrons

We have analyzed the angular distribution of background neutrons. The ISS completes an orbit of the Earth every 90 minutes. Therefore we considered the angular distribution of background neutrons about the Z-axis over this time period. Figure 5 shows the distribution on the θ - ϕ plane. Figure 6 shows the energy distribution of background-neutron-induced protons measured by the *rangemethod*. Figure 7 shows the same plot as Figure 5, but for the short period 21:32-21:40 UT, which is 90 minutes after the flare onset time of 20:02-20:10 UT. This data is used to estimate the background during the flare onset time.

4 Solar Flares observed on March 7, 2011

On March 7 2011, a middle class solar flare was observed. According to GOES satellite data, the intensity of the flare was M3.7; it started at 19:43 UT and reached a maximum at 20:12 UT. Since launching, we have tried to observe every solar flare with an intensity above M2, as recorded by GOES observations. This was the first solar flare for which our sensor detected signals associated with solar neutrons. The signal was not extremely strong but the statistical significance was 8σ .

In the previous conference in Beijing, we were surprised to learn that the Fermi-LAT satellite observed long lasting GeV gamma-rays as a result of this flare [?]. It was unclear until now if solar neutrons were observed during the very intensive solar flares. The Solar Dynamical Observatory data indicated an energetic coronal mass ejection (CME) in association with this flare [?]. Therefore we think that protons in the CME were accelerated and back scattered, causing some protons to hit the solar surface, producing neutrons and gamma-rays. More detail of the production mechanism has been provided in another paper [?].

In Figure 8, we present the signals detected by the SEDA-FIB. To estimate the background involved in the solar cone, it is useful to use the data after 90 minutes presented in Figure 7. The expected arrival direction of neutron-induced protons is shown in Figure 8 by the red line. At that time, the direction of the Sun was 57 degrees on the Y-Z plane, which hardly changed during the time of measurement. We

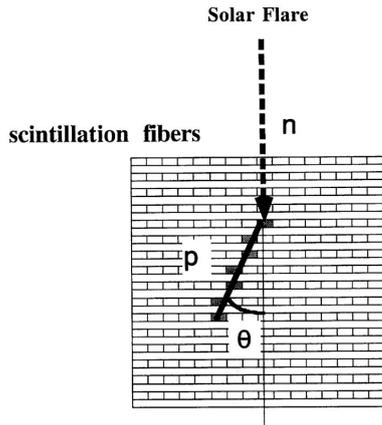


Fig. 1: The schematic view of the sensor of SEDA-FIB. The FIB detector is composed of 16 layers of X-segmented and 16 layers of Y-segmented scintillation arrays. The thickness of one layer is 3 mm. The sensor can identify the incoming direction of neutrons using this segmented structure.

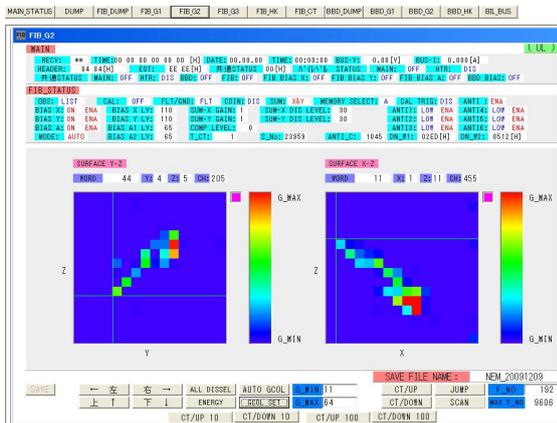


Fig. 2: Typical example of neutron detected by SEDA-FIB. A Bragg peak can be recognized. The color corresponds to the energy loss of protons in each scintillation bar.

have plotted the solar position from 19:49 to 20:02 UT by the open brown squares in Figure 8. Solar neutron with 80 MeV need 13 minutes more flight time than the light.

The same selection criteria was applied to the data sets between 20:02-20:10 UT (flare time) and 21:32-2140 UT (off-flare time as presented in Figure 7). Then, we can say that solar neutrons have been observed with a statistical significance of 8σ .

5 Conclusions

Solar neutrons were detected by the SEDA-FIB onboard the ISS. This may be the first time solar neutrons from M-class solar flares have been detected. From the data observed by the Fermi-LAT satellite, it is probable that these neutrons were produced by the back scattered protons accelerated in a CME by the shock acceleration mechanism. They are not produced by the impulsive phase associated with the largest class solar flares as previously observed.

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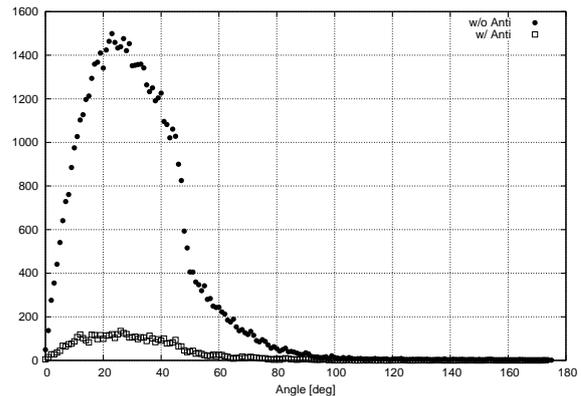


Fig. 3: MC results for the expected angular distribution of protons induced by incoming neutrons inside the sensor with an incident energy of $E_n=80$ MeV. The black circles and white squares correspond to events without the anti-counter and with the anti-counter, respectively.

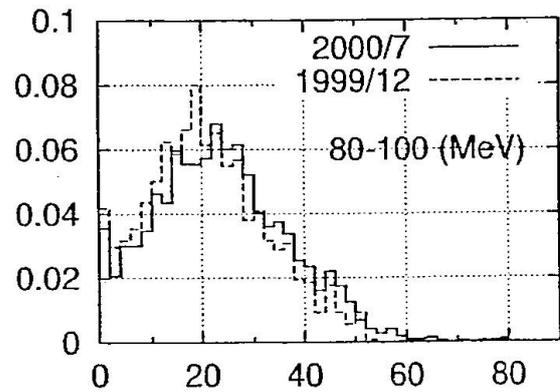


Fig. 4: Experimental results for angular distribution of protons induced by incoming neutrons with the incident energy of 80-100 MeV. The vertical axis represents the number of events normalized by the total event, while the horizontal axis presents the scattering angle in the unit of degrees.

data every day. The authors also thank Dr. M. Fujii of FAM science for providing software.

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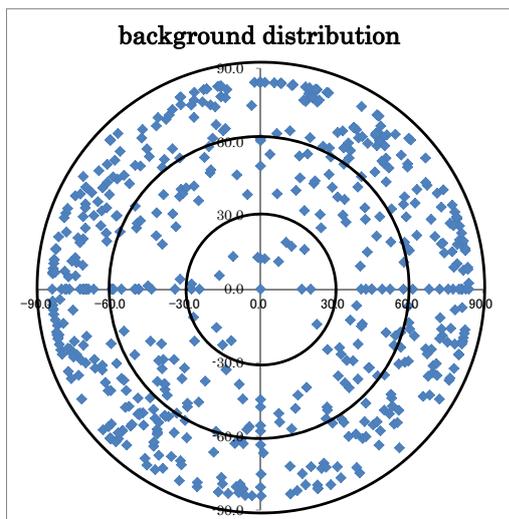


Fig. 5: Angular distribution of background-neutron-induced protons plotted on the θ - ϕ plane. The data was taken during one orbit (90 minutes) of the ISS. A uniform distribution can be seen.

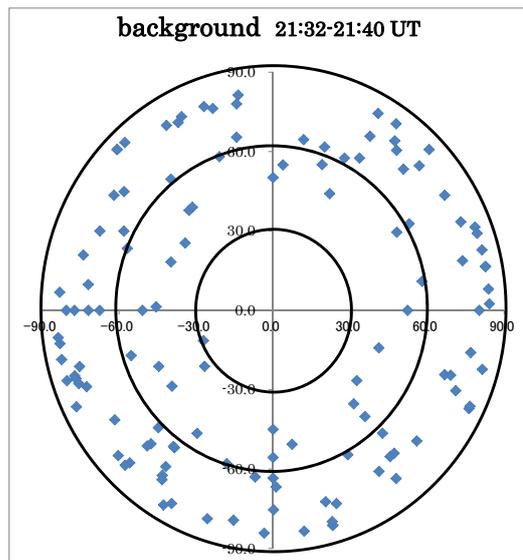


Fig. 7: Angular distribution of background-neutron-induced protons plotted on the θ - ϕ plane. The data was taken 90 minutes after the flare onset time of 21:02-21:40 UT.

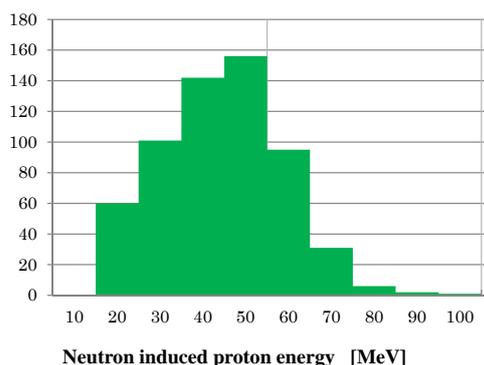


Fig. 6: Energy distribution of above 90 minutes background-neutron-induced protons, based on the measured range. The horizontal axis represents the proton kinetic energy in MeV, while the vertical axis indicates the number of events.

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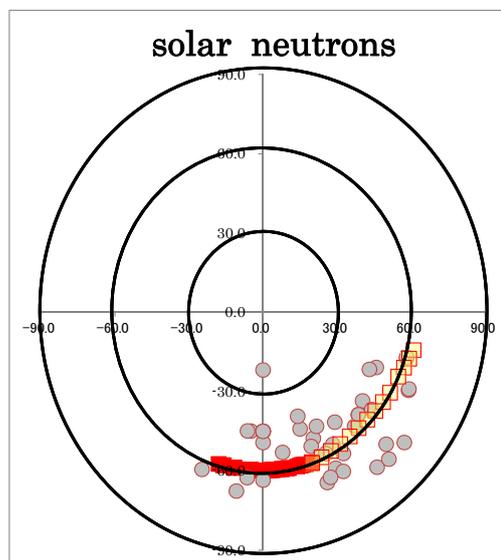


Fig. 8: Angular distribution of neutron-induced protons plotted on the θ - ϕ plane. The data was taken during the flare onset time 20:02 to 20:10 UT on March 7 2011. The the red line represents the direction of the Sun from 20:02 to 20:10 UT, while open brown squares present the solar position from 19:49 to 20:02 UT when neutrons departed from the Sun.