RESEARCH ARTICLE

Development of Neutron Detectors and Measurement of Cosmic-Ray Neutrons

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Abstract

We have developed several neutron spectrometers and dosemeters, such as Phoswich-type spectrometer, Bonner sphere spectrometer and two-type dosemeters of high-efficiency type and lightweight type.

The Phoswich-type spectrometer consists of EJ309 organic liquid scintillator fully covered with EJ299-13 plastic scintillator. Both scintillators emit light outputs of different decay time, 3.5 ns of EJ309 and 285 ns of EJ299-13. Signals of neutrons and photon events are derived from only the inner liquid scintillator and those from charged particles are the sum of both scintillators. Signals from non-charged and charged particles therefore have small and large tail components, respectively, which enables the identification of incident particles. This detector was used to measure cosmic-ray neutrons and photons on board the aircraft over Japan in 2008.

We also developed Bonner sphere spectrometer using only four polyethylene moderators, 1,5 cm, 3 cm, 6 cm, and 9 cm thickness, covered with a spherical ^{3}He counter for environmental neutron measurement on earth. This compact-type detector was modified for use in space by JAXA (Japan Aerospace Exploration Agency) in Japan Experiment Module (JEM) Kibo of ISS (International Space Station) and is continuously operating to send the cosmic-ray neutron data from ISS above about 400 km from the earth.

High-efficiency dosemeter was used for balloon experiment in 2004. The altitude variation of cosmic neutron dose rates was measured up to 25 km altitude over Japan. Recently, a lightweight dosemeter of only 2 kg has been developed and its energy response was investigated to neutrons from thermal to 300 MeV energies. This lightweight dosemeter can be widely used in nuclear facilities and accelerator facilities even in space.

Key words: cosmic neutrons, Phoswich-type detector, Bonner sphere detector, altitude variation, balloon experiment, air-flight experiment, space station experiment high-efficiency dosemeter, lightweight dosemeter

1. Introduction

Neutron measurement is still a difficult problem due to the wide energy range over 10^{12} order of magnitude from thermal to GeV energy and the coexistence of photon radiation. Neutron spectrometry to get the energy spectrum and dosimetry to get the dose equivalent are both indispensable in nuclear facilities and the surrounding environment. Neutrons are also produced in the air by cosmic rays and become important in airplanes and space.

Many neutron spectrometers and dosemeters have been developed. We have developed several neutron spectrometers and dosemeters, including the technique to discriminate other than neutron components. Here in this paper, three detectors, phoswich-type spectrometer[1-3)], Bonner sphere spectrometer[4)] and high-efficiency dosemeter[5,6)] are briefly described which have been used in cosmic-ray neutron measurement, together with the lightweight dosemeter recently developed[7)].

The phoswich-type spectrometer consists of an inner organic liquid scintillator of fast light output pulses fully covered with an outer plastic scintillator of slow light output pulses. Signals of neutrons and photon events are derived from only the inner liquid scintillator and those from charged particles are the sum of both scintillators. Signals from non-charged and charged particles therefore have small and large tail components, respectively, which enables the identification of incident particles. In inner organic scintillator, neutron events emit slower output pulses than photon events, which enables the neutron-photon discrimination. This detector was used to measure cosmic-ray neutrons and photons on board the aircraft over Japan in 2008[3,8)]. We could measure neutron and photon spectra, separately.

We developed Bonner sphere spectrometer using only four polyethylene moderators, 1,5 cm, 3 cm, 6 cm, and 9 cm thickness, covered with a spherical ^{3}He counter for environmental neutron measurement on earth. This compact-type detector was modified for use in space as Bonner ball neutron detector (BBND) by JAXA (Japan Aerospace Exploration Agency) for use in space[8,9)] and is now launched in Japan Experiment Module (JEM) Kibo of ISS (International Space Station). The BBND is now fixed in SEDA-AP (Space Environmental Data Acquisition equipment – Attached Payload) and is continuously operating to send the cosmic-ray neutron data[10,11)].

We also developed high-efficiency dosemeter using ^{3}He counter covered with polyethylene, which is commercially available as NSN2 of Fujielectric Co. Using this dosemeter, we measured the altitude variation of neutron ambient dose equivalent rates up to 25 km height using a balloon over Japan in 2004[12)].

Recently, a lightweight dosemeter of only 2 kg without polyethylene moderator has been developed and its energy response was investigated to neutrons from thermal to 300 MeV energies[7)]. This is commercially available as NSN3 from Fujielectric Co.

2. Development of neutron detectors

2.1. Phoswich spectrometer[1-3)]

The phoswich-type spectrometer consists of a 121.7 mm diam by 121.7 mm thick EJ309 (ELJEN Technology, USA) organic liquid scintillator fully covered with a 15 mm thick EJ299-13 plastic scintillator and optically coupled to a single photomultiplier (R1250, Hamamatsu Photonics, Japan)[2)], as shown in **Fig. 1**. Both scintillators emit light outputs of different decay time, 3.5 ns of EJ309 and 285 ns of EJ299-13. Signals of neutrons and photon events are derived from only the inner liquid scintillator and those from charged particles are the sum of both scintillators. Signals from non-charged and charged particles therefore have small and large tail components, respectively. In the inner organic scintillator, neutron events emit slower output pulses from recoil protons of about 30 ns than photon events from Compton electrons of about 3.5 ns. These differences in the light-decay time constant make it possible to separate pulses of these three different particle species, charged particles, photons and neutrons, by integrating the charge of the signal over different gate intervals. Output signals from the phoswich detector were acquired using the data acquisition device with a fast analog-to-digital converter.

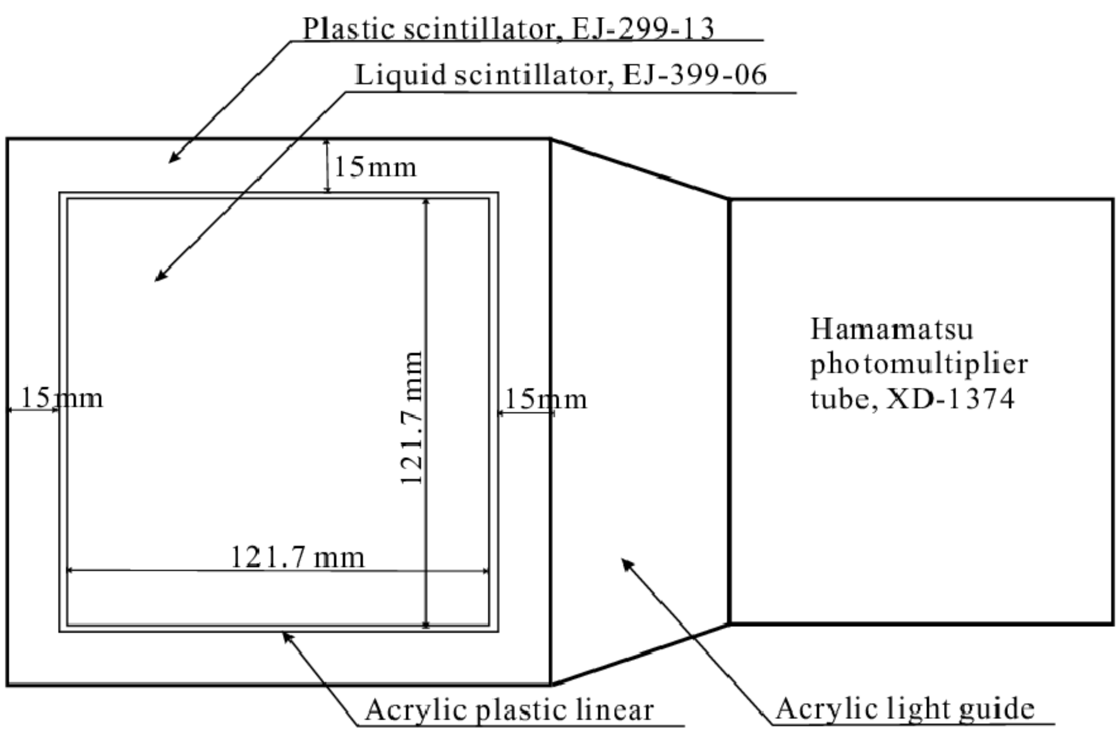


Figure 1. Configuration of phoswich detector [1-3)]

Neutron and photon energy spectra were obtained using the FERDOU unfolding code[13], coupled with the detector response functions calculated with the MCNPX Monte Carlo code[14]. The maximum energies of the response functions are 300 MeV for neutrons and 50 MeV for photons. But for escaping recoil protons from this organic liquid scintillator, the maximum neutron energy to be measured is 180 MeV.

2.2. Bonner sphere spectrometer[4]

The Bonner sphere spectrometer (Bonner ball detector) are widely used in neutron measurement due to its simplicity and the usability over a wide energy range from thermal to MeV, although the energy resolution is poor and an initial guess spectrum is required. We developed the Bonner sphere spectrometer using only four polyethylene moderators, 1,5 cm, 3 cm, 6 cm, and 9 cm thickness, covered with a 5.07 cm diam spherical ^{3}He counter filled with 5 atm ^{3}He gas, as shown in **Fig. 2**. The response functions in the energy range from thermal to 1 GeV were calculated[4,15] with the MCNPX Monte Carlo code. The neutron energy spectrum can be obtained from the SAND-II unfolding code[16] with the response function and the initial guess (default) spectrum.

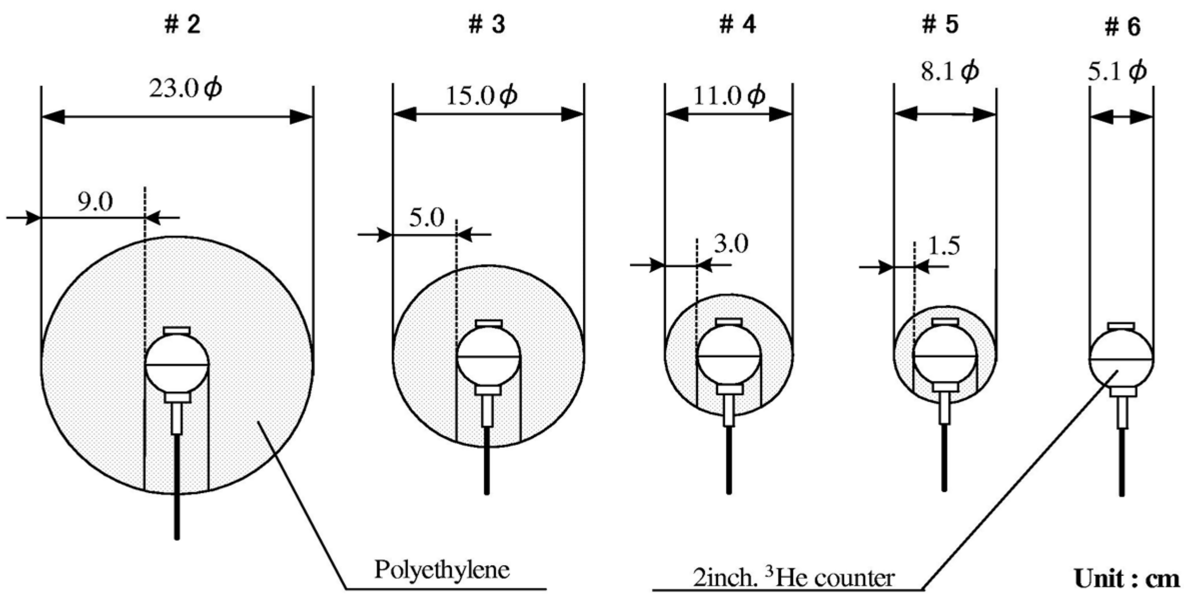


Figure 2. Cross sectional view of Bonner sphere detector [4]

This compact-type Bonner ball detector is now used as Bonner ball neutron detector (BBND) by JAXA (Japan Aerospace Exploration Agency) for use in space[8] and is now fixed in SEDA-AP (Space Environmental Data Acquisition equipment – Attached Payload) in Japan Experiment Module (JEM) Kibo of ISS (International Space Station), as shown in **Fig. 3**. **Figure 4** shows the cross sectional view of BBND sensors. The ^{3}He counters in the center of the six sensors are 2-inch diameter spheres of 6.1 atm gas made by LND Co Ltd. Sensors 2 and 3 are covered with

1-mm-thick gadolinium to block thermal neutrons. The response functions were calculated in the energy range of thermal neutrons up to 100 MeV using the MCNP-4B Monte Carlo code[17)] with considering the mutual interference between 6 detectors of BBND as shown in **Fig. 5**. This BBND was aimed to measure neutron energy spectrum mainly from thermal to 15 MeV, then the response function from 15 MeV to 100 MeV was calculated roughly into one energy group. The detailed description is given in Ref. **8**.

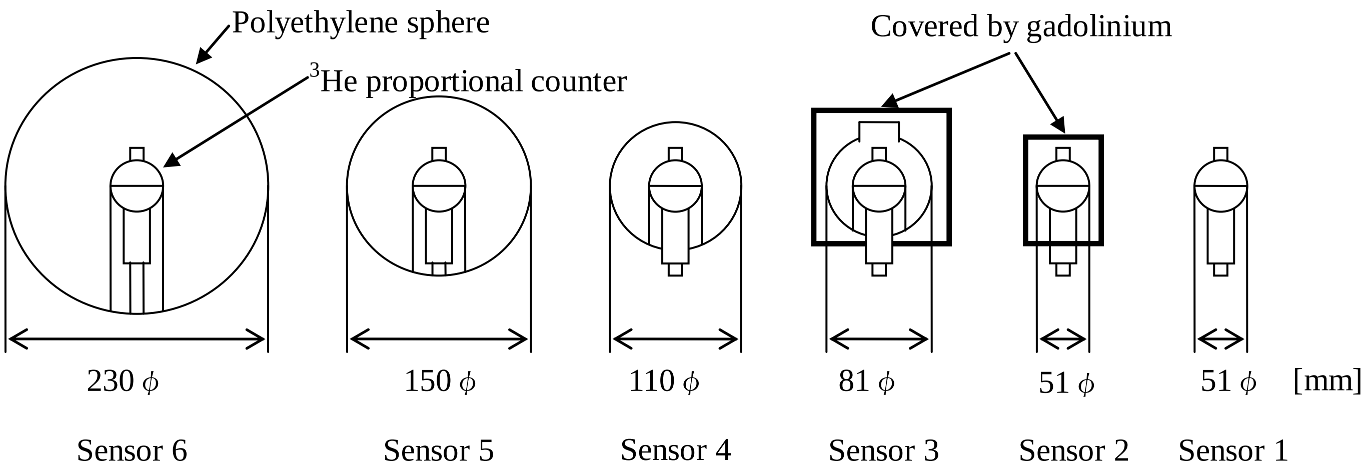


Figure 3. Cross sectional view of BBND sensors [8)]

2.3. High-efficiency dosemeter[5,6)]

Two types of high-efficiency neutron dosemeters were fabricated using 5.08-cm diam counter filled with 10 atm ^{3}He gas and 12.7 cm diam counter filled with 5 atm ^{3}He gas, both covered with polyethylene moderator and internal thermal neutron absorber. **Fig. 6 (a)** shows the cross sectional view of these two dosemeters. The responses of these two dosemeters were compared from thermal up to 15 MeV energy with other commercial dosemeters by experiment and calculation. It was verified that these two dosemeters have about 10 and 70 times higher sensitivities than the widely-used Alnor 2202D dosemeter. The former 5.08-cm diam ^{3}He dosemeter has the neutron sensitivity of 3.5 cps/(mSv/h) and is now commercially available as NSN2 shown in **Fig. 6 (b)** by Fujielectric Co.

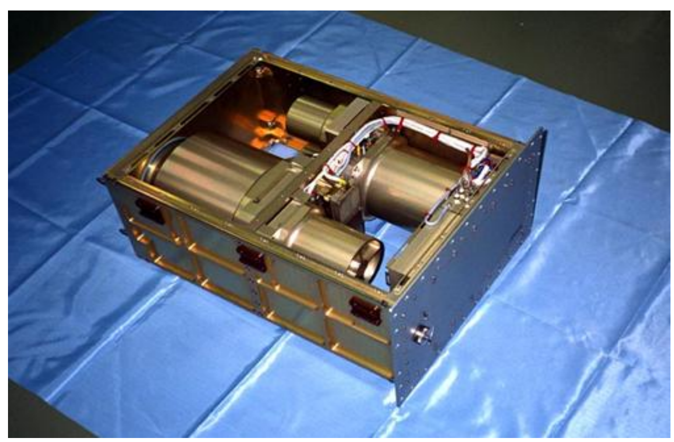


Figure 4. Photograph of Bonner ball, BBND, fabricated by JAXA for use in space on the courtesy of JAXA

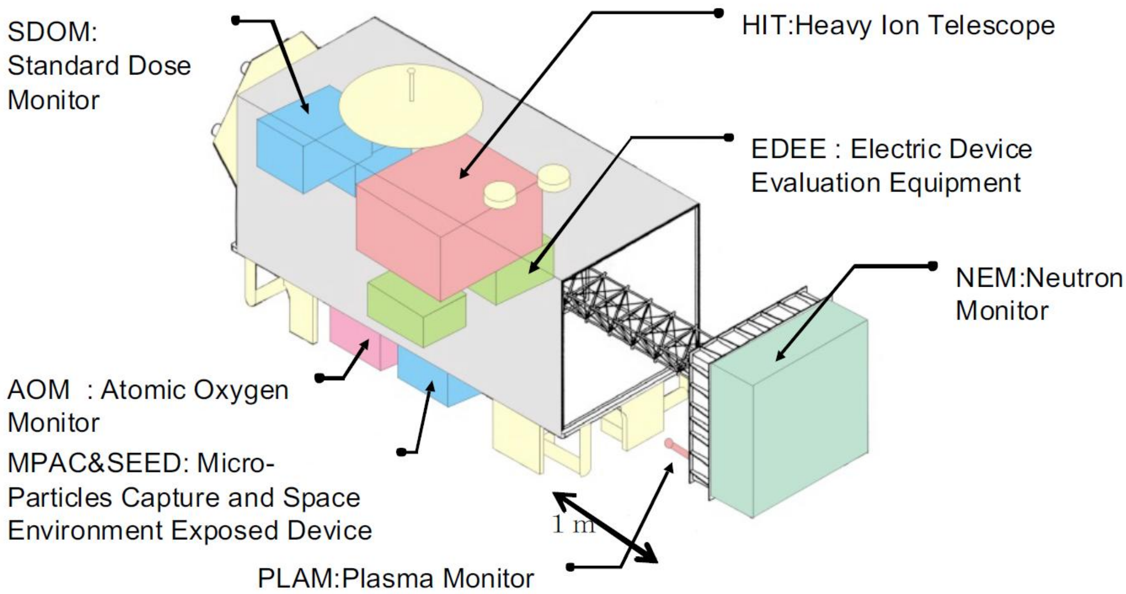
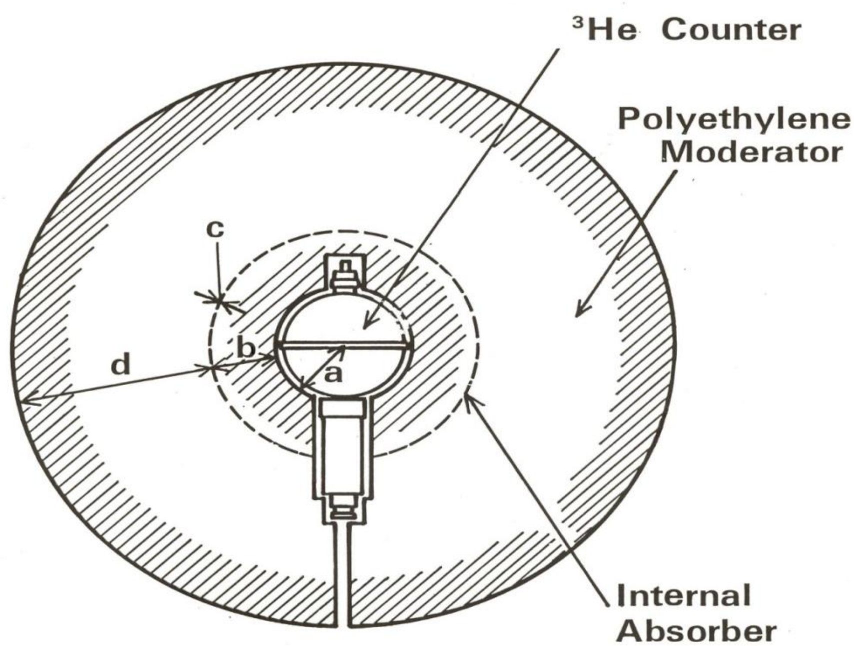


Figure 5. The gross feature of SEDA (Space Environmental Data Acquisition equipment – Attached Payload) [10,11)]



Rem Counter	a	b	c	d	Weight
5.08-cm(2-in.) diam ^{3}He	5.08 cm	4.0 cm	0.114 cm	6.0 cm	8 kg
12.7-cm(5-in.) diam ^{3}He	12.7	4.0	0.114	4.45	13

Figure 6 (a). Cross-sectional view of a high-efficiency dosemeter [5,6)]

Figure 6 (b). Outlook of high-efficiency neutron dosemeter, NSN2 [5,6)]

2.4. Lightweight dosemeter[7)]

Recently, we developed a new light-weight neutron dosemeter of only 2 kg weight without using polyethylene moderator (NSN3 of Fujielectric Co.), as shown in **Fig. 7**. The neutron detector is a gas counter containing a methane gas of approximately 0.4 MPa an a nitrogen gas of approximately 0.1 MPa which are encapsulated in a thin stainless steel vessel as shown in **Fig. 7 (a)**. This dosemeter is now widely used, because the conventional neutron dosemeters using polyethylene moderator are very heavy, about 10 kg or more in weight. The neutron sensitivity of this dosemeter is about 0.3 cps/(mSv/h) which has similar sensitivity as Alnor 2202D dosemeter. The outlook of NSN3 is given in **Fig. 7 (b)**.

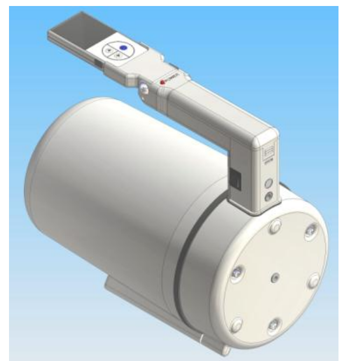


Figure 7 (b). Lightweight neutron dose-meter, NSN3 [7)]

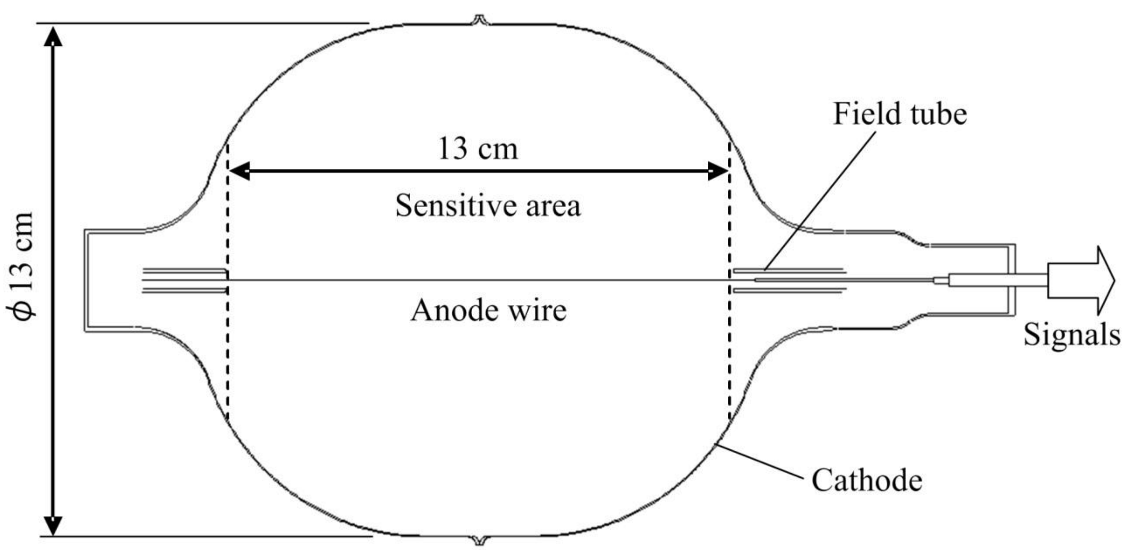


Figure 7 (a). Cross-sectional view of lightweight neutron dosemeter, NSN3 [7)]

3. Measurement of cosmic-ray neutrons

By using these three-type detectors, we did several cosmic-ray neutron measurements on board an airplane, on the ground and in a balloon. JAXA also did the measurements in space. Among the many experiments, the following three results are described here.

3.1. In-flight experiment using Phoswich spectromete[18)]

The phoswich detector was placed on board an MU-300 business jet operated by Diamond Air Service Inc., as seen in **Fig. 8 (a)**. The measurements were performed along the flight route indicated in **Fig. 8 (b)**. The aircraft departed from Nagoya airport (geometrical latitude towards North at 35.2 degrees and longitude towards East at 137 degrees) on February 13, 2008. It reached an altitude of 10.8 km (249 g/cm^2 atmospheric depth) and cruised for about 40 min with constant latitude having 10.2 GV cutoff rigidity during the measurement. The solar activity was close to the minimum.

Figure 8 (a). MU-300 business jet used in the on-board measurement

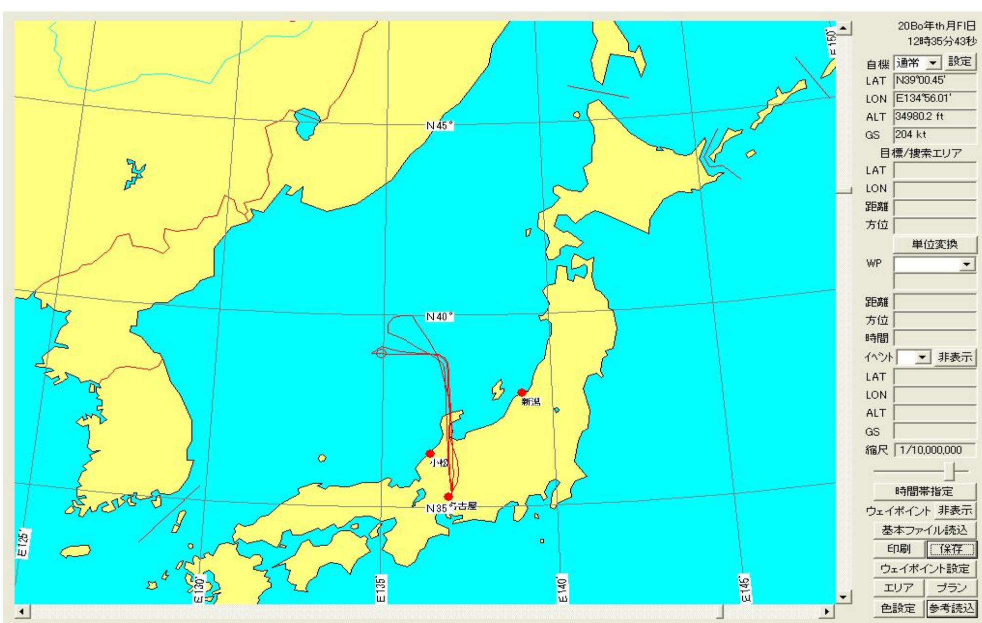


Figure 8 (b). Flight route in the cosmic-ray measurement on February, 13, 2008 [18)].

After discriminating charged particles, neutrons and photons using the differences of their output pulse shapes, we could get the photon energy spectrum from 4 to 50 MeV in **Fig. 9** and neutron energy spectrum from 7 to 180 MeV in **Fig. 10**, separately. In Fig. 9, the measured photon energy spectrum is compared with the spectra calculated using the LUIN2000[19] and EXPACS[20] codes. The measured results fall between the two calculations; they are close to the LUIN2000 calculation at low energies and to the EXPACS calculation at high energies. Our result is also compared with vertical atmospheric photon energy spectrum at the top of the atmosphere (3.5 g/cm^2) using a large-area Compton telescope by Schoenfelder et al.[21] Our result agrees well with their result below 50 MeV. A broad peak around 70 MeV is due to the π^0 decay distribution. In Fig. 10, the neutron energy spectrum measured with the phoswich detector is compared with the spectra calculated using the LUIN2000, EXPACS and RMC model[22], and also other measurements, normalized at this measured location, using Bonner ball detectors (Goldhagen et al.[23], Yajima et al.[24] and Nakamura et al.[25], organic liquid scintillator on the ground (Nakamura et al.[26]) and a double-scatter neutron telescope at the top of the atmosphere (Preszler et al.[27]). The phoswich result in this flight experiment gives a small peak around 10 MeV and a sharp peak around 70 MeV. Both spectra given by the scintillator on the ground and the telescope at the top of atmosphere also have a sharp peak around 70 MeV, while on the other hand, the calculated spectra and the Bonner ball spectra do not give this sharp peak around 70 MeV, but a broad peak around 100 MeV, which may be due to the poor energy resolution and strong dependence on the initial guess spectrum calculated with the simulation model.

3.2. Neutron measurements at different altitudes and in space using Bonner sphere spectrometer[8-11,23-26]

Our developed Bonner ball detector in Fig. 2 were used to measure cosmic-ray neutrons at sea level in Sendai, Japan sequentially from April 2001 up to March 2003[26] and on board the airplane on February 27, 1985[25]. **Figure 11** gives the cosmic-ray neutron energy spectra in lethargy unit at different atmospheric depths (altitudes) around the high cutoff rigidity of 10 to 12 GV obtained by Goldhagen et al.[23] in June 1997 (solar minimum period) and Nakamura et al.[25] on February 27, 1985 (solar minimum period), both on board the airplane, together with the average value at sea level in Sendai, Japan (10 GV) on September 2, 2002 (solar maximum period) by Nakamura et al.[26] The three spectra at high altitudes, 20, 11.28 and 4.88 km, having the similar cutoff rigidity of 12 GV are very close together, although Goldhagens' spectrum is a little bit higher in the energy region lower than the evaporation peak around 1 MeV than the Nakamuras' spectrum. They are also similar to the spectrum measured at sea level having the 10 GV cutoff rigidity in the MeV region which has two eminent peaks around 1 and 100 MeV region, but in the energy region lower than 1 MeV, the spectrum becomes softer with the atmospheric depth and thermal energy peak can be found at sea level, which reflects neutron thermalization through the atmosphere and backscattering from the earth. In spite of big time intervals between these neutron measurements, the energy spectra have not changed very much.

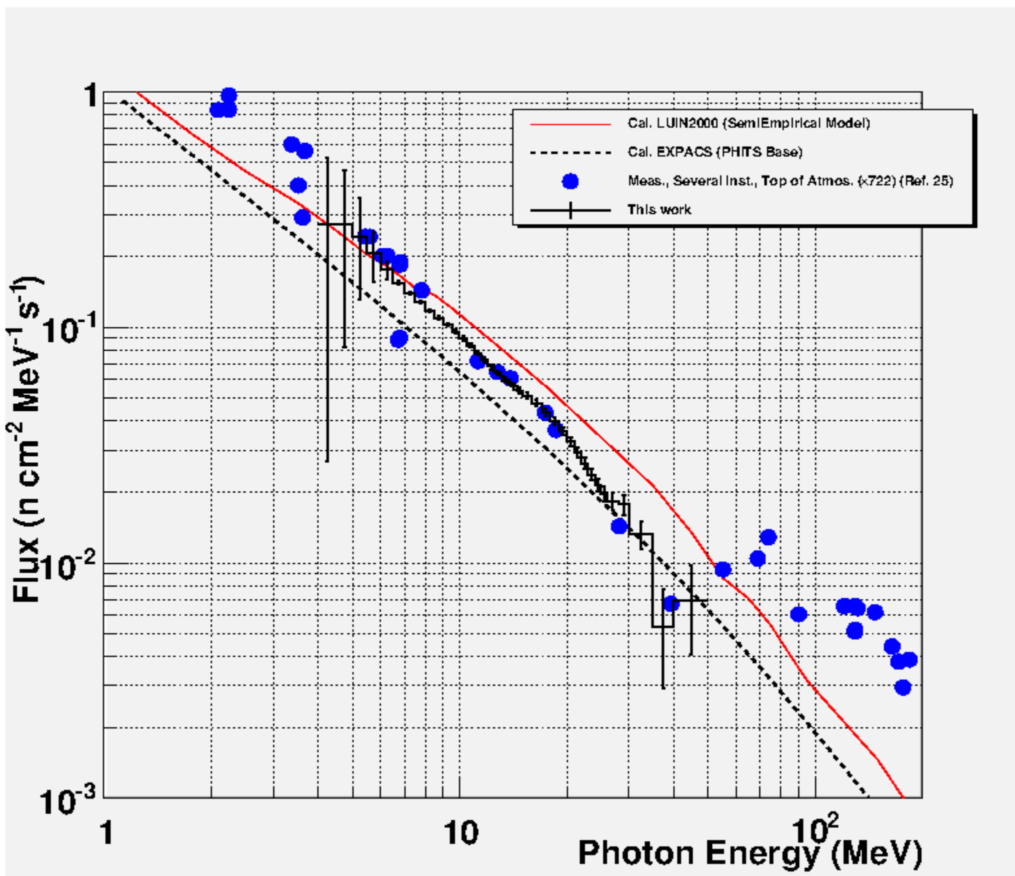


Figure 9. Measured photon energy spectrum [18] from 4 to 50 MeV at an altitude of 10.8 km compared with other calculated [19,20] and measured [21] spectra

The compact-type Bonner ball detector, BBND, settled by JAXA (**Fig. 4**) has been used in real-time measurement on board the space shuttle STS-89 from January 24 to 28, 1998 and in the US module of the ISS from March 23 to July 6, 2001, both above about 400 km above the earth. Now the BBND is continuously operating to send the cosmic-ray neutron data at SEDA-AP of the Japan Experiment Module (JEM) Kibo of ISS. In order to get the neutron spectrum, the 1/E spectrum was used as an initial guess spectrum.

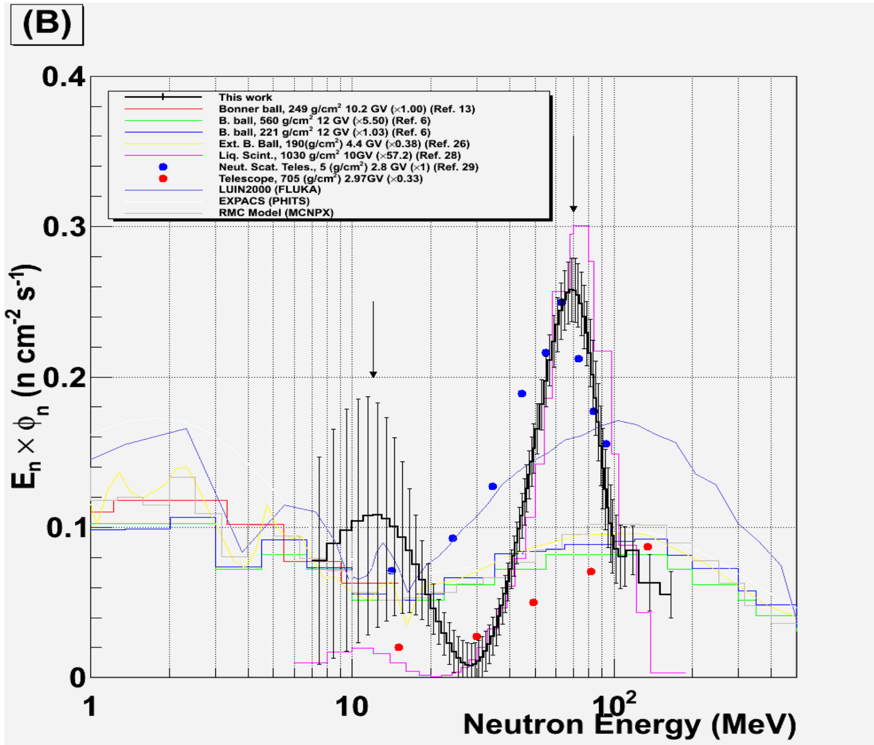


Figure 10. Measured neutron energy spectrum [18] from 7 to 180 MeV at an altitude of 10.8 km compared with other calculated [19,20,22] and measured [23-27] spectra

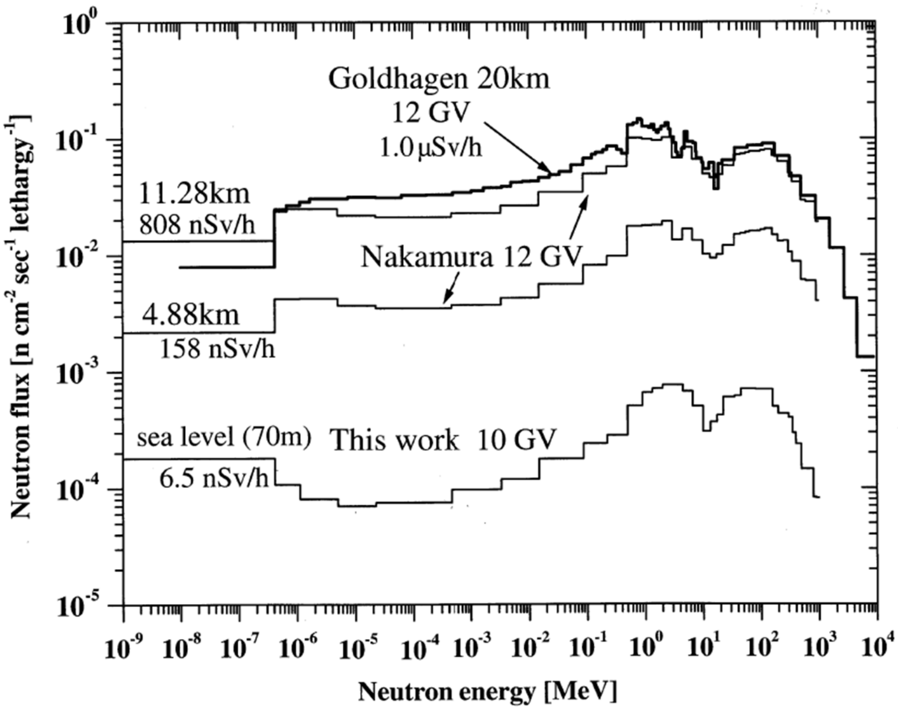


Figure 11. Cosmic-ray neutron energy spectra in lethargy unit at different atmospheric depths (altitudes) around the high cutoff rigidity of 10 to 12 GV obtained by Goldhagen et al. [23] in June 1997 (solar minimum period) and Nakamura et al [25] on February 27, 1985 (solar minimum period), both on board the airplane, together with the average value at sea level in Sendai, Japan (10 GV) on September 2, 2002 (solar maximum period) by Nakamura et al. [26]

Fig. 12 shows the comparison of neutron spectra obtained with BBND at SEDA (extra- vehicle) in January 10 to 30, 2012 and at STS-89 in space shuttle vehicle (intra-vehicle) in January 24 to 27, 1998 [8,9]. Both neutron spectra at extra-vehicle and intra-vehicle are similar, but thermal neutron peak is much larger at extra-vehicle than in intra-vehicle due to moderation through the vehicle wall. Neutron fluxes are 1 to 2 orders of magnitude lower in high energy region and 2 to 3 orders of magnitude lower in low energy region at extra-vehicle position than in space shuttle, because secondary neutrons produced by the vehicle wall are much smaller at SEDA. The neutron flux is smaller in the equatorial region than in the polar region, and much higher in the South Atlantic Anomaly (SAA) region.

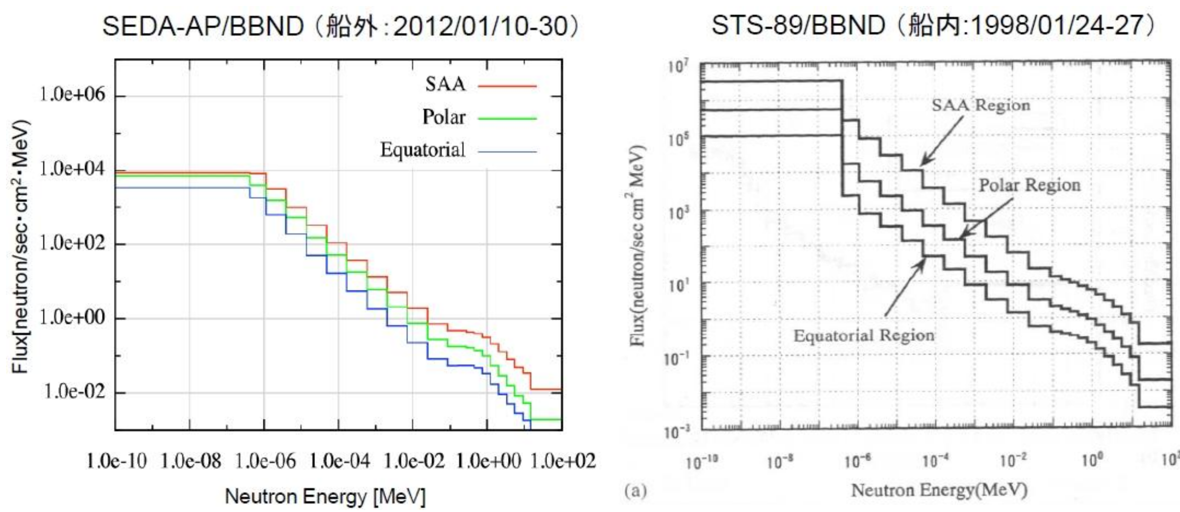


Figure 12. Comparison of neutron spectra obtained with BBND at SEDA (extra vehicle) in January 10 to 30, 2012 on the courtesy of JAXA and at STS89 in space shuttle vehicle in January 24 to 27, 1998 [8,9].

Fig. 13 shows the world map of neutron ambient dose equivalent rate distribution measured at SEDA (extra-vehicle) of ISS from March 15 to March 17, 2012 during no flare event[11], and **Fig. 14** shows the same world map at SEDA from March 7 to March 9, 2012 during flare event[10,11]. The neutron dose rate is generally larger in **Fig. 14** than in **Fig. 13**, especially in the polar region the big increase of secondary neutrons can be clearly seen coming from protons originated from solar flares.

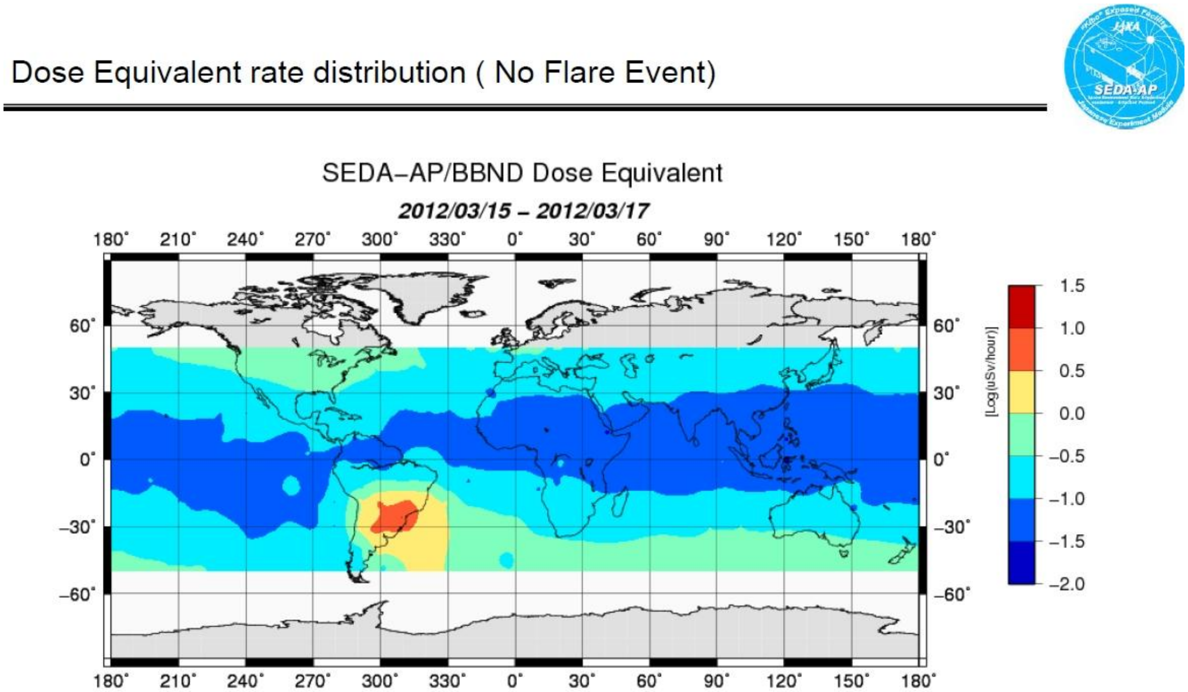


Figure 13. World map of neutron ambient dose equivalent rate distribution measured at SEDA (extra-vehicle) of ISS from March 15 to March 17, 2012 during no flare event on the courtesy of JAXA [11]

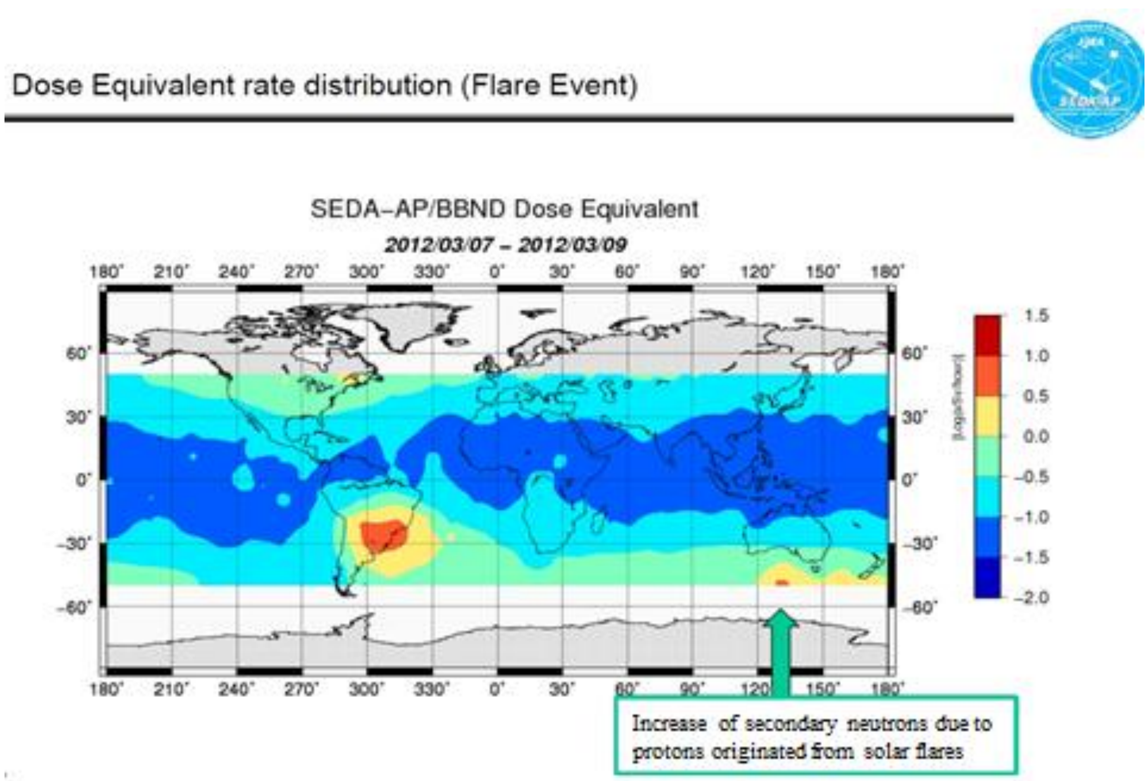


Figure 14. World map of neutron ambient dose equivalent rate distribution measured at SEDA (extra-vehicle) of ISS from March 7 to March 9, 2012 during flare event on the courtesy of JAXA[10,11]

Fig. 15 (a) shows the neutron ambient dose equivalent rate distribution on a world map measured at STS89 in the US space shuttle vehicle (intra-vehicle) of ISS from March 23 to July 6, 2001 just for comparison with **Fig. 14**. The higher values at SAA and polar region are about 10 μSv/h at SEDA and about 80 μSv/h in the vehicle. The former is about one order of magnitude lower than the latter. In both world maps, the flare events are observed in the polar region, especially a big solar flare on April 16, 2001 was observed in the US module, as shown in **Fig. 15 (b)**.

As far as we know, there is no other measurement of the world map of neutron dose rate distribution in space, then this data is the only one measured results and JAXA is now still continuing this measurement at ISS (about 400 km above from the earth).

3.3. Balloon experiment using high-efficiency dosemeter[12)]

We measured the altitude variation of neutron ambient dose equivalent rates using a balloon. A balloon was launched from sea level by JAXA on August 25, 2004 from the Sanriku Balloon Center, Iwate, Japan, and rose to an altitude of 25 km. The geomagnetic latitude here is 30.2 degN and the cutoff rigidity is 9.2 GV. **Fig. 16** shows the flight route of the balloon with the altitude. The balloon was collected on the next day after 1 day flight. The measurement was taken during a period of average solar activity.

Fig. 17 shows the altitude variation of the measured results compared with the EPCARD[28)] and CALI-6[29)] calculations. The agreement between experiment and calculation is quite good. The neutron ambient dose equivalent rate gives the maximum value of 1.5 μSv/h at around 15 to 20 km altitude. This altitude corresponds to the cascade maximum.

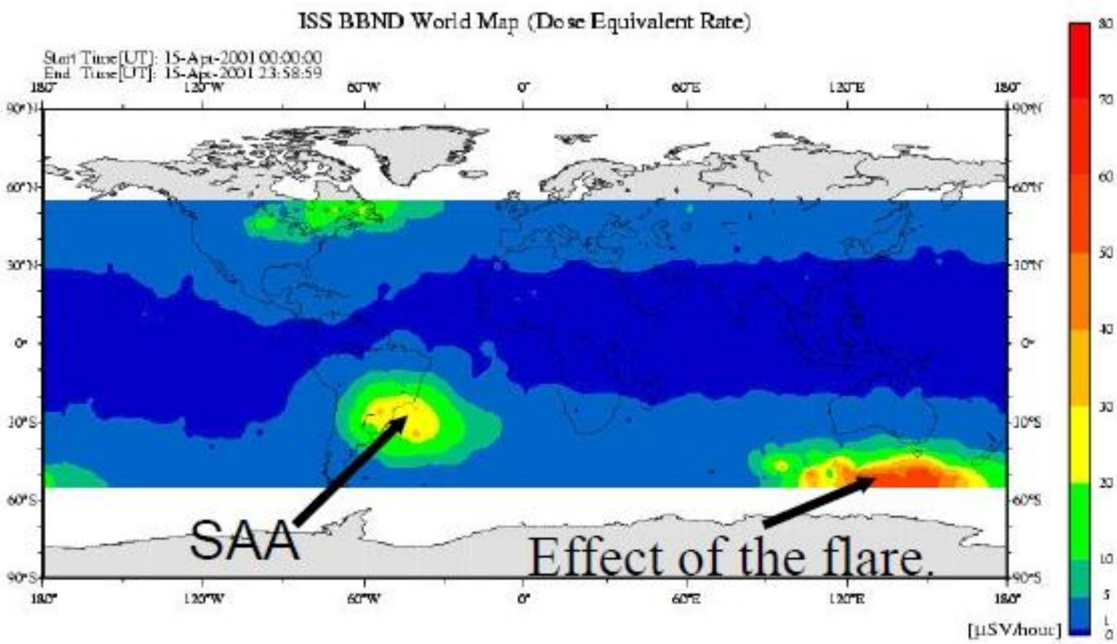


Figure 15 (a). World map of neutron ambient dose equivalent rate distribution measured at STS89 in US space shuttle vehicle from March 23 to July 6, 2001 [8,9)].

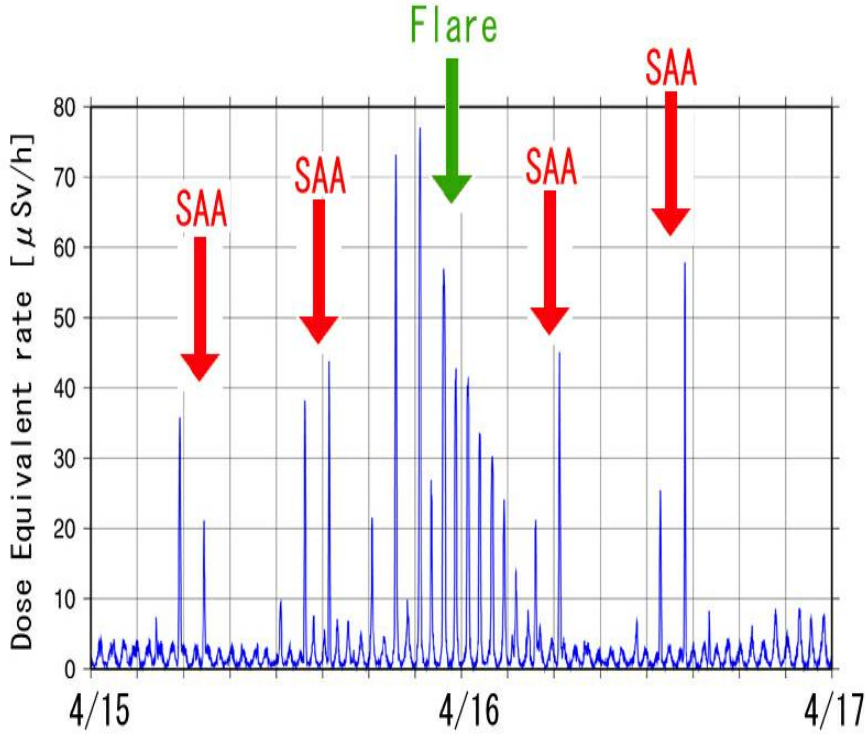


Figure 15 (b). Time variation of neutron ambient dose equivalent rate in the US module at ISS when a big solar flare on April 16, 2001 was observed in the polar region [8,9]

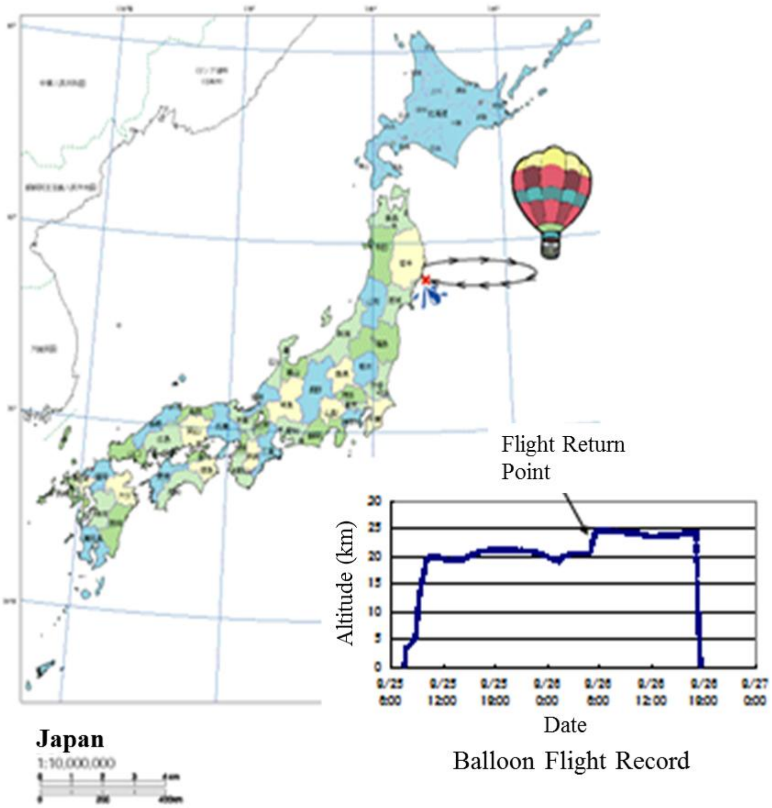


Figure 16. Flight route of the balloon experiment at Sanriku, Japan on August 25, 2004. [12]

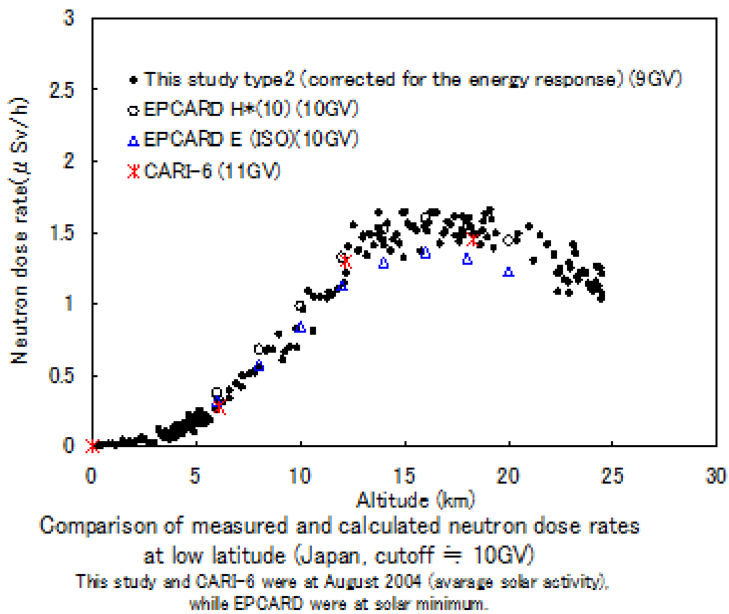


Figure 17. Altitude variation of measured neutron ambient dose equivalent rate [11], compared with calculated results [28,29]

4. Energy response of lightweight neutron dosemeter[7]

We investigated the neutron energy response of lightweight neutron dosemeter, NSN3, in wide energy range from thermal to about 300 MeV neutrons using various neutron fields. **Fig. 18** gives the neutron ambient dose equivalent response relative to the response to ^{241}Am-Be neutron source. Continuous energy neutron fields of graphite-moderated, D_2O-moderated and concrete-moderated neutrons simulate work-place neutron fields, 565 keV, 5 MeV and 14.8 MeV mono-energetic and 134 MeV, 197 MeV and 244 MeV quasi-mono-energetic neutron fields are produced by various nuclear reactions using accelerators. The lightweight neutron dosemeter clearly indicates that neutron energy responses are in good agreement to the ambient neutron dose equivalent within 35% in wide energy region from thermal to about 300 MeV energy, which is much better than the conventional moderated-type neutron dosemeter. From this result, NSN3 can be used in various neutron facilities at nuclear power plants, accelerator facilities, even in space.

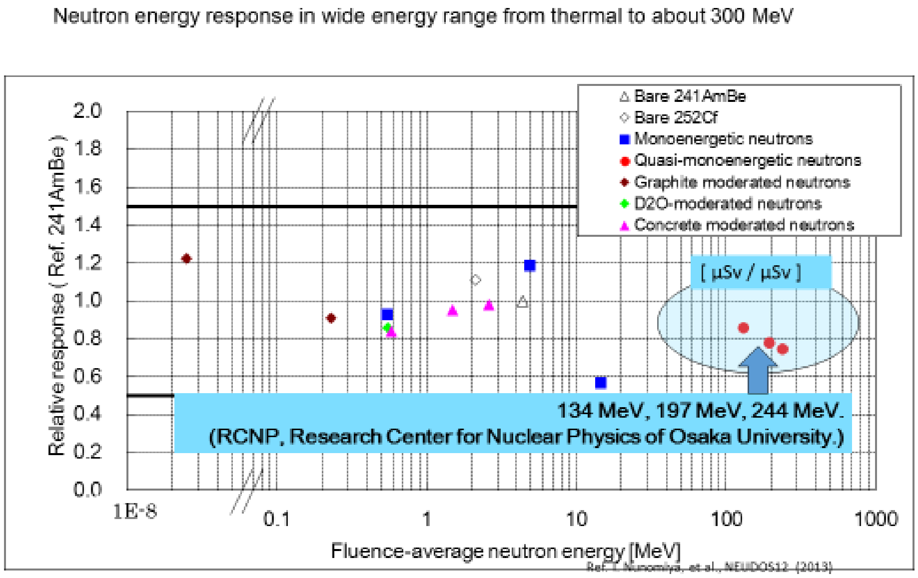


Figure 18. Neutron ambient dose equivalent response relative to the response to ^{241}Am-Be neutron source of lightweight dosemeter, NSN3, over wide energy range from thermal to 300 MeV [7)]

5. Conclusion

Here in this paper, the author reviewed our group work on neutron detector development and its application to cosmic-ray neutron measurements in space. These detector specifications and cosmic-ray neutron measurements together with other detectors and experiments are summarized in the book, Terrestrial Neutron-Induced Soft Errors in Advanced Memory Devices.[30)]

Acknowledgments

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