An Estimation Method of the Lunar Fast Neutron Distribution Derived from a Gamma Ray Spectrometer Using a Ge Crystal. M. Hareyama[1], Y. Karouji[2], S. Kobayashi[1], N. Yamashita[3], O. Gasnault[3], R.C. Reedy[4], N. Hasebe[2] and the KGRS team. [1]Japan Aerospace Exploration Agency, Kanagawa, Japan (hareyama.makoto@jaxa.jp), [2]Research Inst. for Sci. & Eng., Waseda University, Tokyo, Japan, [3]Inst. Rec. Astrophys. Planet., Université de Toulouse / CNRS, France, [4]Planetary Science Institute, Los Alamos, NM, USA.

Introduction: A gamma-ray spectrometer onboard a planetary explorer such as Kaguya (KGRS) [1] and Mars Odyssey (MOGRS) [2] have measured planetary gamma rays to determine the chemical compositions of the planetary surface. The observed spectra include many gamma ray peaks that are induced by neutron interactions with surface materials such as neutron capture and nonelastic scattering as well as gamma rays from natural radioisotopes like 232Th. Therefore, neutron fluxes on the planet are quite important to derive each concentration of elements on the surface from the observed gamma ray data. Since, however, KGRS was not accompanied with a neutron spectrometer, the neutron flux during the observation period have to be estimated from other related data, such as neutron instruments on Lunar Prospector [3]. This report proposes a new method to estimate relative distribution of neutron flux from an observed gamma ray spectrum itself.

Methodology: One of the possibilities is the use of gamma ray lines emitted from detector materials themselves. Since KGRS had a large germanium (Ge) crystal [1], gamma ray lines of Ge are emitted by inelastic scattering inside the Ge detector and detected by the detector itself. The shape of detected peak becomes irregular and is called a "sawtooth peak" in the case of a Ge(n,nγ) reaction. The sawtooth peak is produced when the energy from the de-excitation of an excited Ge level is summed with some of the recoil energy of the Ge nucleus introduced by interactions of fast neutrons in the detector [4]. Therefore, the sawtooth peak has a high-energy tail that depends on the recoil energy distribution relating to the incident neutron energy. In fact, some large sawtooth peaks are shown in the energy spectra obtained by KGRS and Mars Odyssey GRS; whose peak energies are 1039.3 keV from 70Ge(n,nγ), 692 keV and 834.8 keV from 72Ge(n,nγ), 596.1 keV and 1205.2 keV from 74Ge(n,nγ), and 562.9 keV from 76Ge(n,nγ) [2,4]. Because the net counts in these peaks directly reflect fast neutron fluxes, analyses of sawtooth peaks may be practicable to estimate planetary fast neutron fluxes. This work applies a peak fitting method to derive net counts in a sawtooth peak.

In generally, when a detector detects gamma rays, the peak function $P(E)$ as energy E of detected gamma ray peak can be defined as

$$P(E) = \int_0^\infty S(\varepsilon)\eta(E;\varepsilon)d\varepsilon \qquad (1)$$

where $S(\varepsilon)$ is a source function of gamma rays as energy ε and $\eta(E;\varepsilon)$ is a response function for the gamma ray of incident energy ε as detected at energy E. In the case of line gamma rays, since the source function $S(\varepsilon)$ becomes a δ function, $\delta(\varepsilon - E\gamma)$, as $E\gamma$ is an emitting energy from a nuclide, the peak function becomes the response function of its detector. This means that a peak shape made by detected line gamma rays corresponds to a response function of the detector. For the KGRS, the function of an ordinary gamma-ray peak for line gamma ray at energy $E\gamma$ is defined by a Gaussian with exponential low-energy tail due to radiation damage, as presented in [2].

As mentioned above, a sawtooth peak is made by the sum of the line gamma energy with the recoil energy of the Ge nucleus associated with the Ge(n,nγ) reaction in the Ge detector. Here, since the distribution of recoil energy is assumed to exponentially decrease with a factor of $1/\langle T_{Ge}\rangle$, which is called *effective* recoil energy in this report, the source function for the sawtooth becomes $S(\varepsilon) = 0$ for $\varepsilon < E\gamma$ and $S(\varepsilon) = \exp\{-(\varepsilon - E\gamma)/\langle T_{Ge}\rangle\}$ for $\varepsilon \geq E\gamma$. Thus, the peak function of sawtooth peak is derived from Eq.(1) with the response function of the detector and the source function above.

Property of Peak Function: The shapes of this peak function are shown for some parameter sets as energy resolution of σ in keV (standard deviation of Gaussian part of the response function), degree of radiation damage of ρ in keV (low energy tail of the response function) and *effective* recoil energy of $\langle T_{Ge}\rangle$ in keV (high energy tail of the source function) with the ordinary peak shape as line gamma rays in Fig.1. As clearly seen, every peak top of sawtooth peaks shifts to high as comparing with that of ordinary peak corresponding to line gamma-ray energy as $E\gamma$. Though the peak top energy depends on parameters, the peak top energy is several keV higher than the emitting energy of line gamma ray for every case given parameter set, which are typical values in KGRS.

The length of the high-energy tail basically depends on $\langle T_{Ge}\rangle$ only, and dependencies on σ and ρ are negligible in the KGRS case. This means that setting of baseline or continuum part in actual observed gamma ray spectrum is very sensitive to the estimated $\langle T_{Ge}\rangle$.

Peak Fitting: In this report, a sawtooth peak of 834.8 keV from 72Ge(n,nγ) observed by KGRS is selected to check the proposal method. Around this energy region, there are three big ordinary peaks as Al(n,nγ) at 843.8 keV from mainly satellite body, Fe(n,nγ) at 846.8 keV and 228Ac of Th series at 911.2 keV from the Moon, and, furthermore, a medium peak of 209Bi(n,nγ) at 896.2 keV coming from the anti-coincidence BGO scintillator surrounding the Ge crystal detector that are seen. Therefore, it is easy to cross-check on maps derived by this method later. The peaks are assigned about 30 peaks in total from 800 keV to 920 keV of the sawtooth region. Most peaks are radioactive nuclides from spallation of Ge and Bi in Ge and BGO detector itself by interaction of cosmic rays and/or fast neutrons [2,5] and are not very large peaks except for a few peaks.

To map the sawtooth information, we fit the peaks in individual map bins. To help the fitting code to find a solution, σ and ρ are fixed by using ordinary peaks around the sawtooth of interest. The sawtooth peak position is fixed on a long cumulation time spectrum. One additional parameter is introduced to adjust to the specific shape of the sawtooth peak: the *effective* recoil energy $<T_{Ge}>$. A total of 30 parameters were derived for each spectrum, including sawtooth peak areas and recoil energies. If it is confirmed that the dependence of $<T_{Ge}>$ with local lunar chemical composition is negligible, then the total sawtooth peak areas will be map as the most relevant information.

When the gamma ray spectra of the whole moon and 8 pixels of 90 degree width obtaied by KGRS are fitted by this method, the observed spectra were well reconstructed and net counts of three big peaks and the sawtooth peaks look consistent.

Summary: This work showed the possibility of sawtooth fitting to estimate lunar fast neutron flux. Global distribution map of lunar fast neutrons and neutron flux variation during the observation period of Kaguya will be presented in the near future by applying this method to KGRS data. These results will become possible to correct flux variation of fast neutron on region and time for estimation of lunar elemental concentration.

References: [1] Hasebe N. et al. (2009) *J. Phys. Soc, Jpn., Suppl. A78*, 18. [2] Evans L.G. et al. (2006) *JGR, 111*,E03S04. [3] Maurice S. et al. (2004) *JGR, 109*,E07S04. [4] Brückner J. et al. (1987) Proc. Lunar Planet. Sci. Conf. 17th, *JGR 92*, E603. [5] Weidenspointner G. et al. (2003) *A&A 411*, L113.

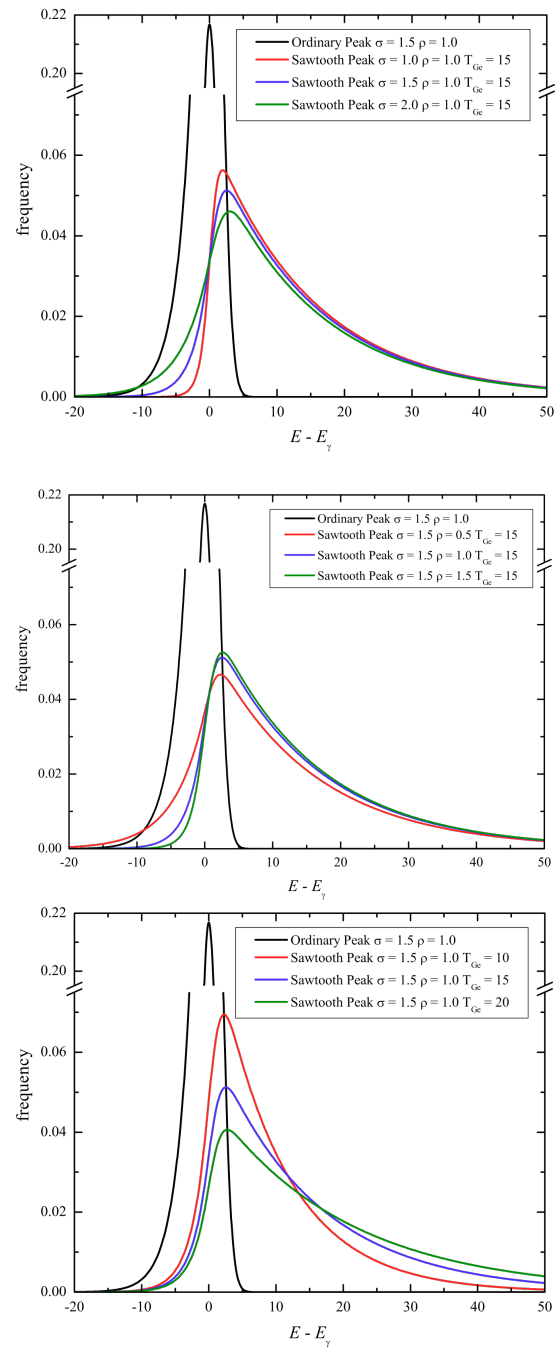

Fig.1 Sawtooth peak shapes with various parameter set. Peak areas are normalized to 1.