PLANETARY GAMMA-RAY IMAGER USING HIGH PRESSURE XENON TIME PROJECTION CHAMBER. N. Hasebe1, N. Yamashita1, M. –N. Kobayashi1, T. Miyachi1, M. Miyajima1, O. Okudaira1, S. Kobayashi1, T. Hosojima 1, K. N. Pushkin 1, C. Tezuka 1, T. Doke 1, and E. Shibamura 2, 1Advanced Research Institute for Science and Engineering, Waseda Univ., 3-4-1, Okubo, Shinjuku, Tokyo 169-8555 Japan (nhasebe@waseda.jp), 2College of Health Science, Saitama Prefectural Univ., 820 Sannomiya, Koshigaya, Saitama 343-8540.

Introduction: Explorations of lunar and planetary surfaces by gamma-ray spectroscopy have been obtaining excellent results in recent missions [1,2]. However, due to the difficulty of gamma-ray collimation, the spatial resolution of gamma-ray spectrometers is not comparable to X-ray, visible, UV, or IR cameras. Compton Telescopes cannot uniquely identify the arrival direction of a single incident gamma ray, and are only applicable for point-like sources. The spatial resolution of a conventional omnidirectional gamma-ray spectrometer is a function of the altitude. In order to survey small to medium sized geological structures, the improvement in spatial resolution of gamma-ray observation is desired. By introducing a new method of gamma-ray measurement, gamma-ray imaging camera is considered for planetary science.

Design of a New Detector: High-pressure Xe time projection chamber (HPXe-TPC) is a new generation of gamma-ray camera based on a principle of Compton Telescope [3,4]. HPXe-TPC can uniquely determine the arrival direction of each gamma ray.

Basic Design. As a detection medium, xenon gas is employed. It has an energy resolution of ~2% at 662 keV, approximately one third of that of NaI(Tl) scintillators. Unlike germanium detectors, HPXe-TPC has a high stability against radiation damage [5], and has a wide operating temperature of up to ~100 degrees Celsius [4]. A schematic drawing of HPXe-TPC is shown as Fig. 1. It consists of a tracker and an absorber, both filled with Xe gas with the pressure of 1~3 MPa and 5 MPa, respectively. After Compton scattering in it, the tracker measures energy of a recoil electron and a position where the reaction took place by detecting 3-dimensional trajectory of the electron. The absorber measures the total energy of scattered gamma ray and interaction position as well.

Determination of Interaction Position. Two electrodes, cathode and position sensitive electrode (PSE) are placed in the tracker and absorber. When a gamma ray experiences Compton scattering with a Xe atom, a recoil electron and scintillation light are generated. The scintillation light is detected by avalanche photodiodes and used as a timing signal for arrival time of a gamma ray. The electronic field is applied between cathode and PSE and secondary electrons ionized by the recoil electron drift toward PSE. PSE measures the energy of recoil electron in the tracker, as well as that of the scattered gamma ray in the absorber are proportional to the number of ionization electrons and simultaneously measured.

Reconstruction of the Arrival Direction: Assuming that the momentum and energy of orbital electrons are negligible, the scattering angle of a gamma ray $\theta$ and the projected angle of the recoil electron $\phi$, as shown in Fig. 2., are described by the conservation laws of energy and momentum, which are given by

$$\cos \theta = 1 + \frac{m_ec^2}{E_1 + E_2} - \frac{m_ec^2}{E_2}$$

and

$$\cos \phi = \frac{E_1}{\sqrt{E_1^2 + 2m_ec^2E_2}} + \frac{m_ec^2E_1}{(E_1 + E_2)\sqrt{E_1^2 + 2m_ec^2E_1}}$$

where $E_1$ is the energy of the recoil electron, $E_2$ is that of the scattered gamma ray, $m_e$ is the rest mass of an electron, and $c$ is the velocity of light. Note that Compton scattering occurs on a plane formed by momentum vectors of the recoil electron and the scattered gamma ray. Therefore the arrival direction of incident gamma rays can be determined uniquely with HPXe-TPC.

Angular Resolution: The uncertainty of the arrival direction of incident gamma rays is governed by the accuracy of reconstructed trajectory of recoil elec-
trons. The trajectory of a single gamma ray is reconstructed as an arc of a circle, giving the maximum angle uncertainty $\Delta \omega_{\text{max}}$. Let us define the angular resolution of observation by HPXe-TPC $\Delta \omega_{\text{obs}}$ as the difference in angle between $\Delta \omega_{\text{max}}$ and the original direction of the gamma ray. It will be expressed as

$$\Delta \omega_{\text{obs}} = \Delta \omega_{\text{max}} - \Delta \omega_{\text{max}} \sin \left( \frac{\tan(\Delta \eta)}{\sin(\theta + \phi)} \right)$$ (3)

where $\Delta \eta$ is the angular uncertainty of the trajectory of the recoil electron. $\Delta \eta$ is caused by multiple scattering of electron in Xe, $\Delta \eta_e$, and errors in detecting position by electrodes, $\Delta \eta_p$.

Recoil electrons are scattered in the Xe gas and gradually lose their initial projected directions. The PSE interval should be small enough and the mean free path of Compton scattered electrons in Xe gas should be long enough to lose their initial directions. The trajectories of the electrons in Xe gas were simulated using the Monte Carlo simulation library Geant4 release 6.2 and are shown in Fig. 3. In this calculation, 1 MeV electrons pass through Xe gas with the density of 0.06 g/cm$^3$. In Fig. 4, apex angles with which a cone covers 50% of incident electrons inside are plotted as a function of tracked length $l$ for various incident energies. It is shown that half of 1 MeV electrons change their directions by less than 7 degrees when traveling 1mm in Xe gas.

The spatial resolution in detecting the reaction position by electrodes, $\sigma_p$, is assumed to be equal among $x$, $y$, and $z$ coordinates for simplicity. $\sigma_p$ is dependent on $l$, the tracked length of electrons at which $E_1$ is determined. Then $\Delta \eta_p$ can be expressed as

$$\Delta \eta_p(l) = \frac{\sqrt{2} \sigma_p}{l} = \frac{d}{\sqrt{6}l}$$ (4)

while $d$ is the interval of electrodes on PSE.

Since $\Delta \eta_e$ and $\Delta \eta_p$ are statistically independent, and $\Delta \eta_e$ is proportional to $l$ while $\Delta \eta_p$ is inversely proportional to $l$, there exists an ideal $l$ value that gives the minimum $\Delta \eta$. With this parameter, $\Delta \eta$ can be substituted to Eq. 3 and $\Delta \omega_{\text{max}}$ can be derived as a function of gamma-ray energy, as shown in Fig. 5 with various electrode intervals.

Conclusions and discussions: In terms of fabrication technique and stability of PSE, $d = 0.5-1$ mm is a reasonable choice. Under such circumstances, the angular resolution $\Delta \omega_{\text{max}}$ is expected to be 3 to 20 degrees, depending on the energy of incident gamma rays, with 50% probability. This angular resolution is equivalent to a spatial resolution of 5 to 40 km in an observation of the Moon at the altitude of 100 km. The nominal spatial resolution of conventional spectrometers would be ~150 km. The new generation gamma-ray camera, HPXe-TPC, will drastically improve the spatial resolution of gamma-ray spectroscopy.