U02-P01　　　　　　　会場:3 階ポスター会場　　　　　　　時間:4 月 28 日 18:15-19:30

# Review of the recent muon radiography observations by using nuclear emulsion detector

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Nuclear emulsion is one of three dimensional particle tracker which have micron position resolution and the feature that no electricity so we can put this detector everywhere easily and also this is suitable for non-fixed point observation.

Several observations for volcanoes were done and will be done from 2011 to 2014. The imaging the of Unzen lava dome, which was formed from 1991 to 1995, was done by Miyamoto et al and they found the detector got many back ground particles and the amount is more than several times than expected muon signal. this implies that we are on the stage of background particle study.

The emulsion cloud chamber (ECC) is a modular structure made of a sandwich of passive material plates such as lead interleaved with emulsion film layers. Nishiyama et al studied the source of background noise in cosmic-ray muon radiography using ECC. They found that the origin of background is expected to be electromagnetic components of air-showers or cosmic-ray muons scattered in topographic material whith momentums is less than 2GeV/c.

The shallow conduit shape of Stromboli will provide the important information for eruption dynamics modeling by Tioukov et al. Hernandez et al put the emulsion detector near the top of summit of Teide volcano to investigate the past eruption histroy of Teide. Teide volcano is located in Teferife, Canary Islands, Spain. They are also under observation of the fault appeared in La Palma, Canary Island, in 1949, which is the sign of huge land collapse or not. The width of the fault is expected to be 1 meter or less, so high position resolution of emulsion detector is suitable for this observation. They will measure the width, delth and the porosity of this fault.

# 宇宙線ミューオンラジオグラフィーと重力異常データの同時インバージョンによる溶岩ドームの３次元密度構造解析
# Simultaneous inversion of muon radiography and gravity anomaly data for 3-D density structural analysis of lava domes

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Cosmic-ray muon radiography (muography) has been utilized for obtaining the density profiles of volcanoes (eg. Tanaka et al., 2007; Lesparre et al., 2010; Cârloganu et al., 2013). Since gravity measurement is also sensitive to the internal density of the Earth, a combination of muography and gravimetry is expected to provide density profiles with fine resolutions (Okubo and Tanaka, 2012). Nishiyama et al. (2014) has developed a simultaneous inversion method of both two data for determining the 3-D density structures of volcanoes and has presented the feasibility of the hybrid measurement through a case study of a small (500 m in diameter) lava dome, Showa-Shinzan, Hokkaido, Japan. This study revealed that a vent extends downward beneath the dome.

We are now planning another hybrid measurement at Tarumai Lava Dome on the Shikotsu caldera, Hokkaido, Japan, in order to perform a comparative study on the internal structures of lava domes. The Tarumai lava dome has formed at the top of Mt. Tarumai during the 1909 eruption. We conducted gravity measurements at 23 stations spanning 1.5 km (NS) x 1.5 km (EW). We are preparing the muography detector for the coming measurement. We report the possible detector sites and the result of the resolution test of this new hybrid measurement.

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U02-P03    会場:3 階ポスター会場    時間:4 月 28 日 18:15-19:30

# ミュオンを用いた地下水状態把握のテスト計測の紹介（いくつかの観測結果を含めて）
# Introduction about test measurement of the muon detection system for monitoring a groundwater (With some observations)

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The technique to radiographically image the internal structure of gigantic objects by utilizing muon's significant penetration power (muography) enabled us to investigate the internal structure of volcanoes and the city foundation with higher spatial resolution than possible with the conventional techniques.

This observation technique is applicable to exploring a large-scale civil engineering structure, the internal state of a base rock, etc. However, feasibility of muographic application to monitoring inside the large-scale civil engineering structure has not confirmed yet. Therefore, we decided to carry out test measurements in order to explore the possibility of muography for monitoring groundwater levels.

We are currently investigating the response of the groundwater levels to major rainfall events in the landslide area. We selected this area as an observation area. The measurement was carried out from the inside of a scupper tunnel in the base rock. Our muon detection system consists of plastic scintillator, photomultipliers (PMTs), and a high voltage (HV) power supply.

The muography detector was installed to the observation site in August, 2012 and measurement was started on the same date.

The result will be compared with the independent measurement results of groundwater levels and soil resistivity in order to quantitatively assess the technological limit of muography.

So far, we obtained the preliminary result that showed variations in the penetrating muon intensity; hence the density as a response of major rain fall events by plotting a moving average of the 48-hour observation time at different time intervals of one hour, two hours, three hours, and six hours. It showed a clear rainfall effect when the time interval is 6 hours. The future prospect includes further case studies for different rainfall-underground water coupling scenarios.

キーワード: ミュオグラフィー, ミュオン観測装置, 地下水位, テスト計測, 地すべり
Keywords: muography, muon detection system, groundwater, test measurement, landslide

歴史的考察から得られるギリシア・パルテノン神殿の耐震性能低下の可能性とミュオグラフィによるその評価について
# A Historical View on the Degradation on Seismic Performance of The Parthenon, Greece and Muography as the Potential Eval

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To reinforce the Parthenon against earthquakes, the process of disassembling and reassembling Doric columns is obligatory. For this, the column strength and durability is required to withstand the reconstruction process. Wooden rods in the dowels of each drum provide the mechanical strength of each column, however some of these rods may have been damaged during the Venetian bombardment of the Acropolis on September 26, 1687. Due to the size of the Parthenon's Doric columns, muography is more appropriate to image the internal structure than conventional radiographic techniques. Muography may be utilized as a non-destructive technique targeting the inside composition of the Parthenon's Doric columns, potentially providing the following information: (1) the durability of the columns against future earthquakes, and (2) the magnitude of the internal damage sustained during the Venetian bombardment. The results of this muographic survey would aid conservator's efforts to protect the Parthenon along with the possibly of applying to other cultural properties. Secondly, the state of the wooden rod inside the column will provide evidence for the time and temperature around the column (based on the geometrical structure and thermal conductivity of the column) which would contribute further evidence to historical discussions particular to the Parthenon, such as estimates of the amount of gun powder stored in the Parthenon by the Ottoman Empire and information on the aforementioned siege. Muography may supplement efforts to preserve and protect the Parthenon as well as contributing to our understanding of the historical events that have occurred in this ancient structure.

キーワード: 歴史的考察, 耐震性能低下, パルテノン神殿, ミュオグラフィ
Keywords: a Historical View, the Degradation on Seismic Performance, the Parthenon, Muography

U02-P05　　　　　　会場:3 階ポスター会場　　　　　時間:4 月 28 日 18:15-19:30

# Geo-neutrinos and reactor anti-neutrinos expected in Daya Bay II and in LENA
# Geo-neutrinos and reactor anti-neutrinos expected in Daya Bay II and in LENA

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BALDONCINI, Marica[1*] ; ESPOSITO, Juan[2] ; LUDHOVA, Livia[3] ; MANTOVANI, Fabio[1] ; RICCI, Barbara[1] ; XHIXHA, Gerti[1] ; ZAVATARELLI, Sandra[4]

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Geo-neutrinos produced by beta decays occurring in $^{238}$U and $^{232}$Th decay chains are presently detected via inverse beta reaction in liquid scintillation detectors (KamLAND and Borexino). Geo-neutrinos are a unique direct probe of our planet's interior since they instantaneously bring to the Earth's surface information concerning the total amount and distribution of U and Th in the crust and in the mantle, which are thought to be the main reservoirs of these elements. The geo-neutrino spectrum allows to discriminate the different Th and U components. Measuring geo-neutrino fluxes and spectra can shed light on the radiogenic contribution to the terrestrial heat power and on the Earth's nowadays composition, providing a direct test of the Bulk Silicate Earth models and giving additional constraints on the Earth's evolution models.

A better discrimination among different Earth's global models can be reached combining the results from several sites: new measurements of geo-neutrino fluxes are highly awaited from experiments entering operation, such as SNO+, or proposed to the scientific community, as LENA or Daya Bay II. In particular, LENA and Daya Bay II would provide a substantial increase of the detection sensitivity and of the event rate thanks to their large target masses (50 kton and 20 kton, respectively) compared to the 1 kton mass of KamLAND and SNO+ and to the 0.3 kton of Borexino.

The main background in geo-neutrino measurements is due to the electron anti-neutrinos produced by nuclear power plants, which are the strongest man-made anti-neutrino sources. Many fission products decay through beta processes with the consequent emission of electron anti-neutrinos, the so called reactor anti-neutrinos. The reactor anti-neutrino spectrum covers an energy range extending up to about 8 MeV, which results in a significant overlap between geo-neutrino and reactor anti-neutrino signals in the geo-neutrino energy window (1.8 － 3.3 MeV). The events of reactor anti-neutrinos are strongly dependent on the distance of the closeby commercial nuclear power plants. Therefore, a careful analysis of the expected reactor anti-neutrino event rate at a given experimental site is mandatory.

In this framework, we estimate the expected reactor anti-neutrino signals at ongoing geo-neutrino experiments sites, in particular at Pyhasalmi and JUNO (Jiangmen Underground Neutrino Observatory), which are the candidate sites for hosting the LENA and Daya Bay II experiments, respectively. The inputs required to evaluate the reactor anti-neutrino flux come from neutrino properties, nuclear physics in the reactors and features of nuclear power plants. In our calculation we take into account the three neutrino oscillation mechanisms in vacuum, the most updated reactor anti-neutrino spectra and standard fuel compositions. According to the International Atomic Energy Agency (IAEA) database, we use detailed information on the locations and on the monthly time profiles of the thermal power for each nuclear core.

In Table 1 we report the expected geo-neutrino and reactor anti-neutrino signals for different locations, expressed in TNU (Terrestrial Neutrino Units). Nuclear power plants data refer to IAEA database reporting information of year 2012, when all of the Japanese nuclear power plants were still switched off. The ratio between the expected reactor anti-neutrino signal in the geo-neutrino energy window ($R_G$) and the expected geo-neutrino signal (G) is calculated all over the world in order to produce a $R_G$/G map. The values of $R_G$/G for future sites (Phyasalmi and JUNO) are almost comparable to the operating ones (LNGS and Kamioka), with a slight preference for the Finnish location. The total uncertainty on the reactor signal predictions is on the order of 5%: among all the accounted sources of uncertainties, the ones giving the main contributions originate from the $\theta_{12}$ mixing angle, the anti-neutrino spectrum, the fuel composition and the thermal power.

キーワード: geo-neutrino, anti-neutrino from reactor, neutrino detector
Keywords: geo-neutrino, anti-neutrino from reactor, neutrino detector

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| Sites | R [TNU] | $R_G$ [TNU] | G [TNU] | $R_G/G$ |
|---|---|---|---|---|
| LNGS | $85.8 \pm 4.6$ | $22.8 \pm 1.1$ | $40.3^{+7.3}_{-5.8}$ | 0.6 |
| KAMIOKA | $70.1 \pm 3.7$ | $18.7 \pm 1.1$ | $31.5^{+4.9}_{-4.1}$ | 0.6 |
| SUDBURY | $174.6 \pm 9.0$ | $43.1 \pm 2.1$ | $45.4^{+7.5}_{-6.3}$ | 0.9 |
| PHYASALMI | $69.2 \pm 3.7$ | $17.5 \pm 0.8$ | $45.3^{+7.0}_{-5.9}$ | 0.4 |
| FREJUS | $587.9 \pm 31.0$ | $134.0 \pm 7.1$ | $42.4^{+7.6}_{-6.2}$ | 3.2 |
| HOMESTAKE | $27.7 \pm 1.5$ | $7.3 \pm 0.3$ | $48.7^{+8.4}_{-6.9}$ | 0.1 |
| HAWAII | $3.4 \pm 0.2$ | $0.9 \pm 0.04$ | $12.0^{+0.7}_{-0.6}$ | 0.1 |
| CURACAO | $9.5 \pm 0.5$ | $2.5 \pm 0.1$ | $29.3^{+4.2}_{-3.3}$ | 0.1 |
| JUNO | $99.0 \pm 5.1$ | $27.4 \pm 1.4$ | $39.7^{+6.5}_{-5.1}$ | 0.7 |

**Table 1:** Comparison between expected reactor (R) and geo (G) antineutrino signal. $R_G$ indicates the reactor signal expected in the geo neutrino energy window ($E_{\bar{\nu}} < 3.26$ MeV). 1 TNU = 1event/year/$10^{32}$ protons.

# Towards a refined regional geological model for predicting geoneutrinos flux at Sudbury Neutrino Observatory (SNO+)

STRATI, Virginia[1]* ; HUANG, Yu[2] ; MANTOVANI, Fabio[1] ; SHIREY, Steven B.[3] ; RUDNICK, Roberta L.[2] ; MCDONOUGH, William F.[2]

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The SNO+ detector is the redeployment of the illustrious Sudbury Neutrino Observatory (SNO) at SNOLAB in Ontario (Canada). After the substitution of heavy water ($D_2O$) with liquid scintillator ($CH_2$) inside the inner vessel, in 2014 the 1 kton detector will come on-line and together with KamLAND in Japan and Borexino in Italy will accumulate geoneutrino events. Geoneutrinos are electron antineutrinos originating from beta decays of natural radioactive nuclides in the Earth interior. A fraction of them, generated from $^{214}$Bi and $^{234}$Pa of $^{238}$U decay chain and from $^{228}$Ac and $^{212}$Bi of $^{232}$Th decay chain, are above the threshold for inverse beta reaction on free protons and can be detected by SNO+. Geoneutrinos are a real time probe of Earth interior, because the flux at the terrestrial surface depends on the amount and distributions of U and Th in the Earth's reservoirs. To extract global information such as terrestrial radiogenic heat power or to test compositional models of the Bulk Silicate Earth (BSE), the regional contribution to the geoneutrino signal has to be controlled by study of regional geology.

We present the 3-D refined geological model of the main reservoirs of U and Th in the regional crust extended for approximately $2 \times 10^5$ km$^2$ around SNOLAB, including estimates of the volumes and masses of Upper, Middle and Lower crust, together with their uncertainties. According to the existing global reference model (Huang et al., 2013), this portion of the crust contributes for 43% of the total expected signal at SNO+. The remaining contributions come from the far field crust (34%), from continental lithospheric mantle (5%) and from the mantle (18%). Since SNO+ will accumulate statistically significant amounts of geoneutrino data in the coming years, the calculated signal that is predicted to be derived from the lithosphere can be subtracted from the experimentally determined total geoneutrino signal to estimate the mantle contribution.

The main crustal reservoirs are modeled by identifying three main surfaces: the Moho discontinuity, the top of the Lower Crust and the top of the Middle Crust. About 400 depth-controlling data points obtained from deep crustal refraction surveys and from teleseismic receivers are the inputs for the spatial interpolation performed with the Ordinary Kriging estimator. This method takes into account the spatial continuity of the depths and it provides the uncertainties of the crustal volumes. The Upper Crust is further modeled in detail combining information from vertical crustal cross sections and Geological Map of North America at 1:5,000,000 scale. Seven sub-reservoirs with distinctive characteristics lithologies, metamorphism, tectonic events and chemical composition are identified. The density and the abundances of U and Th in the seven sub-reservoirs are evaluated from the published litho-geochemical databases, including analyses of representative outcrop samples. The Middle and Lower Crust densities and radioactivity contents are evaluated from seismic constraints.

The numerical 3D model consists of about $9 \times 10^8$ cells of 1 km × 1 km × 0.1 km dimensions. For each of them geophysical information, such as latitude, longitude, depth and reservoir type, are combined with estimates of the U and Th abundances to predict the geoneutrino signal at SNO+ originated from the regional crust. The total geoneutrino signal at SNO+ is about 12% less than that calculated using the global reference model (Huang et al., 2013).

キーワード: geoneutrinos, SNO+, uranium, thorium, geological modeling
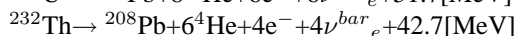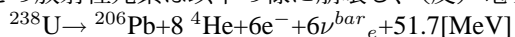Keywords: geoneutrinos, SNO+, uranium, thorium, geological modeling

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## 地球ニュートリノの測定精度向上に向けたカムランドのアップグレード計画
## Upgrade plan of the KamLAND detector for improvement of sensitivity to geo-neutrino

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　素粒子の一種であるニュートリノは、弱い相互作用を通してのみ他の粒子と反応する。東北大 RCNS は、大型ニュートリノ検出器 KamLAND を用いてニュートリノ科学について研究している。 地球内部の放射性熱源の推定や地球モデルの構成元素への制限をするには、地球内部で起こるベータ崩壊によって生じる地球ニュートリノを測定することが唯一の方法である。

　　KamLAND 検出器は低エネルギーの反電子ニュートリノを検出することが可能な点が特徴である。$^{238}$U や $^{232}$Th などの放射性元素は以下の様に崩壊し、（反）電子ニュートリノ（地球ニュートリノ）を放出する。

$^{238}$U→ $^{206}$Pb+8 $^4$He+6e$^-$+6$\nu^{bar}_e$+51.7[MeV]

$^{232}$Th→ $^{208}$Pb+6$^4$He+4e$^-$+4$\nu^{bar}_e$+42.7[MeV]

　地球ニュートリノを測定することで、放射性熱源について直接知ることができる。実際に KamLAND は過去に地球ニュートリノの測定を通して結果を出していて、$^{238}$U や $^{232}$Th による放射性熱源が $20.1_{-9.1}^{+9.1}$ TW であるとの推定を行った。これは地球の全熱流量である $44 \pm 1$TW よりも明らかに小さい結果である。

　　KamLAND 検出器の感度上昇を目標として、アップグレード計画（KamLAND2）が進行中である。例えば、大光量液体シンチレータ、集光ミラー、高量子効率の光電子増倍管（PMT）、カメラ、光るフィルムなどが挙げられる。

　　KamLAND2 実験においてはエネルギー及び位置分解能の向上が見込まれていて、これによって地球ニュートリノがより高い精度で、かつ多くの統計を得ることが可能となる。すなわち、モデルの検証や $^{238}$U と $^{232}$Th 比を求めるための精度があがる。

　　本講演では将来計画とその R&D に関して発表する。

Keywords: geo-neutrino

# カムランドにおける次期エレクトロニクス
# The next-generation KamLAND electronics

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KamLAND was constructed to detect the low energy anti-neutrinos. And then, KamLAND detected reactor neutrinos and solved solar neutrino problem on 2003. And furthermore, KamLAND detected geo-neutrinos for the first time in the world on 2005. Currently, KamLAND has already been beginning to search several new physics. However, searching new physics in the detector of 10 years ago is difficult. So, it is necessary to update the detector. We are planning to update the KamLAND. As this updating, KamLAND electronics will be renewed using the latest technologies. The next-generation KamLAND electronics will certainly contribute to geoscience.

Keywords: Neutrino detector, Data taking, electronics

U02-P09　　　　　　　　会場:3 階ポスター会場　　　　　　　時間:4 月 28 日 18:15-19:30

# イメージング検出器
## Imaging detector

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　地球ニュートリノは、地球の熱源の約半分を占める放射性元素（ウラン、トリウムなど）から放出され、ニュートリノの透過力の高さから、マントル内部の寄与も観測できる可能性がある。2005 年に、1 キロトン液体シンチレータ検出器「カムランド」（岐阜県飛騨市）で地球ニュートリノが初めて観測されて以来、地球の熱源を探る新たな観測手段として注目されている。現在では、イタリアの液体シンチレータ検出器「ボレキシーノ」も加わり、「2 点観測」を行っているが、観測点がまだ不足していることに加え、ニュートリノの到来方向を測定できていないことが、データの精密化の障壁となっている。我々は、地球ニュートリノの到来方向測定のための新たな検出器開発を進めており、カムランドへの実装を目指している。地球ニュートリノ検出の際に放出される中性子の放出方向を検出するため、中性子捕獲断面積の大きいリチウム 6 を溶かし込んだ液体シンチレータの開発、中性子捕獲位置を精密測定するため、液体シンチレータを撮影するイメージング検出器の開発などを行い、それらを組み合わせて地球ニュートリノの方向検出を目指している。本ポスターでは、イメージング検出器について解説する。シンチレータの微弱な発光を 1 光子単位で検出し、発光点を精度よく決定するため、受講面積が大きく収差が小さい光学系、量子効率が高く、位置分解能にすぐれた光検出器を組み合わせる必要がある。現在、もっとも有望な設計として、直径 50 cm のミラーを用いた光学系と、256 チャンネル・マルチアノード光電子増倍管を組み合わせたデザインを中心に、開発状況、実装計画、期待される成果を述べる。

キーワード: ニュートリノ, 地球ニュートリノ, 放射性熱源
Keywords: neutrino, geo-neutrino, radiogenic heat source

U02-P10 会場:3 階ポスター会場 時間:4 月 28 日 18:15-19:30

# 方向検出のためのリチウム液体シンチレーターの開発
# Li loaded liquid scintillator for directional measurement

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　現在の液体シンチレータを用いた電子型反ニュートリノの検出では、陽子による逆 $\beta$ 崩壊反応により放出される陽電子と中性子の遅延同時計測によって強力なバックグラウンド除去を行うことが出来る。そしてそれによって低エネルギー領域での電子型反ニュートリノの観測を行うことが可能となっている。

　その反面現存する検出器では水チェレンコフ法のように電子型反ニュートリノの飛来方向を知ることが出来ない。しかし、陽電子の反応点と中性子の捕獲点を観測することによって電子型反ニュートリノの飛来方向を知ることは可能である。低エネルギーにおけるニュートリノの飛来方向の観測が可能になればニュートリノを観測対象ごとに区別することができるようになり、従来の観測よりもさらに高い精度での観測が出来ると期待される。

　液体シンチレータによって電子型反ニュートリノの飛来方向を検出するためには、次の三つの問題を解決することが重要である。それは方向情報を失う前に中性子を捕獲すること、中性子捕獲反応点で発光現象を起こすこと、そしてその発光点を高い位置分解能で検出する装置を作ることである。

　現在の液体シンチレータでは逆 $\beta$ 崩壊により放出される熱中性子が陽電子により捕獲されるまでに平均 200 $\mu$ s かかり、陽電子によって捕獲された際に放出されるエネルギーは 2.2MeV の $\gamma$ 線となってしまう。これでは、放出される熱中性子は十数 cm 拡散し位置情報はぼやけてしまい、2.2MeV の $\gamma$ 線は約 40cm も移動するために中性子吸収点を特定することが出来なくなってしまう。今回、この問題を解決するために中性子捕獲断面積が 940barn で陽子の 0.3barn に比べて非常に大きく、中性子捕獲時に液体シンチレータ中を長距離移動出来ない $\alpha$ 線を放出する $^6$Li を導入した液体シンチレータを開発した。この新しい液体シンチレータにより上記の二つの問題点を解決し、同時に開発中である高い位置分解能で発光点を検出する装置と組み合わせることによって電子型反ニュートリノの飛来方向を検出することが出来ると期待される。

　本講演では独自の方法で開発したリチウム含有液体シンチレータについて講演する。

キーワード: 地球ニュートリノ
Keywords: geo-neutrino

U02-P11 　　　　　会場:3 階ポスター会場 　　　　　時間:4 月 28 日 18:15-19:30

## 大型ニュートリノ実験による地球トモグラフィー
## Tomography of the earth with large-scale neutrino experiments

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Experimental techniques to study inside of the Earth have been developing remarkably in the past decades. For example, in-situ x-ray diffraction measurements under high-pressure and high-temperature opened new era for studying about possible chemical components and structures of deep Earth. In the next ten years, we will obtain yet another technique for direct measurements of the Earth's interior.

Probing inner structures of the Earth with neutrinos has been discussed for more than 30 years. Neutrinos are chargeless particles and have very small cross-sections. They normally penetrate the Earth without any interaction, and from the rare interactions that do occur we obtain information on the density profile of the Earth's interior. However, the elusive characteristic of neutrinos poses a challenge for detecting them at experimental sites. To compensate for the small interaction cross-section, one needs a large volume neutrino detector.

The IceCube[1] neutrino observatory, completed in 2011 and has 1 cubic kilo-meter volume of detector size, is a possible candidate for this study. Current status of a study for measuring the core density of the Earth with atmospheric neutrino will be presented.

Another characteristic of neutrino is that they change their flavor periodically (neutrino oscillation). These oscillation patterns are affected by the density profile of electrons along the path of the neutrino. Comparisons between the Earth's mass-density profile and the electron-density profile give us ratio profiles of atomic number vs mass number (A/Z), which contains information of chemical composition of the Earth.

It is crucial to use a specific energy range for source neutrinos in order to perform the neutrino oscillation tomography. For Earth's core, the energy range is ~1GeV to 30GeV. To detect the GeV-range neutrinos with sufficient statistics, next-generation experiments Hyper Kamiokande[2] and PINGU[3] have been proposed. Possible discrimination powers of some chemical models of the Earths core will be discussed.

Fig.1
Left: Exclusion of a pyrolite core model with respect to a pure iron core a time range of ten years. Right: The accuracy, measured in units of sigma, of the Z/A measurement for the assumption of an iron core. Calculated for PINGU[3].

References

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キーワード: ニュートリノトモグラフィ, ニュートリノグラフィ, アイスキューブ
Keywords: neutrino tomography, neutrino radiography, IceCube

U02-P11          会場:3 階ポスター会場          時間:4 月 28 日 18:15-19:30

U02-P12　　　　　　　会場:3 階ポスター会場　　　　　　　時間:4 月 28 日 18:15-19:30
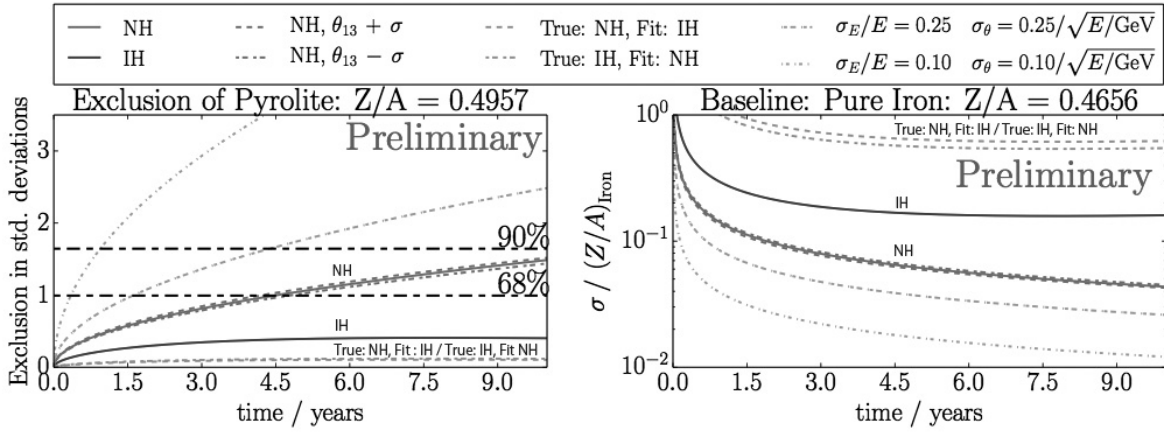
# 多層式ミュオグラフィ検出器による有珠山の内部構造探査
# Muographic imaging of Usu volcano with a multilayer detector

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Usu volcano is one of the most active volcanoes in Japan and has erupted for four times in the recent 100 years (1910, 1943, 1977-1978 and 2000). In the 1977-1978 eruption, 18 craterlets and a U-shaped fault were formed in the summit crater. The eruption also caused the deformation in the summit crater area with a diameter of 1.8 km and formed an upheaval called Usu-Shinzan.

Preceding studies suggested that the cooling magma intrusion with a height of 600 m and a width of 300 m was located below the Usu-Shinzan by magnetotelluric soundings (e.g. Ogawa et al., 1998, Matsushima et al., 2001). And Yokoyama and Seino (2000) built a tilt model to interpret the formation of Usu-Shinzan. In this model, a block with a width of 800 m tilted approximately $11^o$ on a pivot at a depth of 800 m. So, in the present work, we conducted the muographic imaging (radiography with cosmic-ray muon) of Usu volcano to confirm the existence of magma intrusion beneath Usu-Shinzan.

But there is the issue of background (BG) noise of muographic imaging for a large volcano (>1 km thick). Since the integrated intensity of traversing cosmic-ray muons steeply decays as a function of the thickness of the target, the signal-to-noise (S/N) ratio also decreases seriously as the size of target becomes larger, and thus the density distribution cannot be accurately measured at a large volcano. The background (BG) noise that reduces the S/N ratio mainly consists of the fake tracks that are generated by the accidental coincidence of the electromagnetic (EM) shower particles. The values of BG noise were $10^{-6}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ (Lesparre et al., 2012) and $10^{-7}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ (Carloganu et al., 2013). BG noise of $10^{-7}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ corresponds to integrated cosmic-ray muon intensity after traversing 1 km of 2.65-g cm$^{-3}$ rock.

In order to solve this problem, we developed a novel muon detection system that consists of multiple layers of position sensitive detectors (PSDs) in conjunction with a trajectory analysis method to effectively reduce the BG noise. In this method, the EM shower-originated fake tracks are rejected by requesting a linear trajectory for a muon event (linear cut method) since EM shower particles randomly hit each PSD layer and make a non-linear trajectory in the detection system. This detection system was applied to Usu volcano, Hokkaido, Japan to image its internal density structure (the spatial distribution of the density). In this measurement, we utilized a muon detection system that consisted of 7 layers of PSDs. One PSD consisted of x- and y- arrays of plastic scintillator strips with an active area of 1.21 m$^2$ and a segmented area of 10x10 cm$^2$. The angular resolution was +/- 3$^o$. The measurement duration was 1977 hours (82 days).

In this measurement, we compared the integrated cosmic-ray muon intensity traversing 2500 m of 1.5-g cm$^{-3}$ rock with observed data at an elevation angle of 55.6 mrad. Assuming that the residual between the calculated intensity and data is BG noise, we obtained the BG noises of 5.4x10$^{-5}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ with two PSDs and 1.9x10$^{-6}$ cm$^{-2}$ sr$^{-1}$ s$^{-1}$ with seven PSDs. The multilayered muon detector was effective to reduce the BG noise. However, BG noise remains and they may be attributed to another source of BG noise such as upward-going particles(Jourde et al., 2013). This measurement yielded the following results: (A) by analyzing the region that has a thickness of more than 1000 m, we confirmed that our detection system is sensitive to a density variation of 10% in 1300-m rock; and (B) there are high- and low-density anomalies beneath between Oo-Usu and Usu-Shinzan peaks, which is consistent with the magma intrusion and the resultant fault generation suggested by Yokoyama and Seino (2000), Ogawa et al. (1998) and Matsushima et al. (2001).

For the future prospect, we will try to use the shield in order to distinguish the upward-going particles from muons arriving from a volcano side.

キーワード: ミュオグラフィ, ミュオン, ラジオグラフィー
Keywords: muography, muon, radiography