MOON for spectroscopic studies of double beta decays and the present status of the MOON-1 prototype detector

H Nakamura, H Ejiri, K Fushimi, K Ichihara, K Matsuoka, M Nomachi, R Hazama, S Umehara, S Yoshida, T Ogama, T Sakiuchi, V H Hai, Y Sugaya and the MOON collaboration

Graduate school of science, Osaka University, Toyonaka, Osaka 560-043, Japan
RCNP, Osaka University, Toyonaka, Osaka 560-043, Japan
IAS, University of Tokushima, Tokushima 770-8592, Japan
RCNS, Tohoku University, Sendai 980-8578, Japan

E-mail: hidehito@fn.lns.sci.osaka-u.ac.jp, ejiri@rcnp.osaka-u.ac.jp, fushimi@ias.tokushima-u.ac.jp, kayoko@rcnp.osaka-u.ac.jp, matsuoka@lns.sci.osaka-u.ac.jp, nomachi@fn.lns.sci.osaka-u.ac.jp, hazama@km.phys.sci.osaka-u.ac.jp, umehara@km.phys.sci.osaka-u.ac.jp, sci@lns.sci.osaka-u.ac.jp, ogama@fn.lns.sci.osaka-u.ac.jp, sakiuchi@fn.lns.sci.osaka-u.ac.jp, vhhai@fn.lns.sci.osaka-u.ac.jp, sugaya@fn.lns.sci.osaka-u.ac.jp

Abstract. The MOON (Molybdenum Observatory Of Neutrinos) project, as an extension of ELEGANT V, aims at spectroscopic studies of double beta decays from $^{100}$Mo with a sensitivity of the Majorana neutrino mass around 30 meV. Measurements with good energy and position resolutions enable one to select true signals and to reject background ones. A prototype MOON detector (MOON Phase-1A) with 142 g $^{100}$Mo was built and is running at the Oto underground laboratory. The present report describes briefly the outline of the MOON project and the present status of MOON-1.

1. Introduction
Recent studies of neutrino oscillations suggest that the effective mass to be studied by neutrinoless double beta decay is of the order of $0.1 \sim 0.02$ eV if the neutrino is a Majorana particle and the mass spectrum is with quasi-degenerate or inverted hierarchy. Thus it is of great interest to study double beta decays with that sensitivity. $^{100}$Mo is shown to have large responses for the double beta decay [1,2]. The MOON (Molybdenum Observatory Of Neutrinos) project is a double beta decay experiment with a few ton of $^{100}$Mo. It aims at spectroscopic studies of the neutrinoless double beta decays with sensitivity to effective mass of $<m_{ee}>=30$ meV. This paper describes the MOON project and the present R&D with the prototype detector MOON Phase-1A.

2. MOON (Molybdenum Observatory Of Neutrinos)
The MOON detector is a multi-layer module with plastic scintillators and enriched $^{100}$Mo foils. It is based on the double beta decay study of $^{100}$Mo by the ELEGANT-V [3]. The $^{100}$Mo foil is interleaved with the plastic scintillators. The MOON experiment is planned to probe the half-life $\sim 10^{27}$ y, which
corresponds to the sensitivity of the effective neutrino mass down to the ~30 meV region. When 2 ton $^{100}$Mo sources are used, 12 decays/year can be expected. In this case, the total area of the Mo foil with 95% $^{100}$Mo will be 5,250 m$^2$ with 40 mg/cm$^2$. A multi-layer structure of plastic scintillators and $^{100}$Mo foils are used for the MOON detector. Two beta rays from $^{100}$Mo foil are detected by two plastic scintillators which are placed above and below the $^{100}$Mo foil. The other plastic scintillators are used as an active shield to reduce the radioactive background (BG) events. Plastic scintillator layers work as a calorimeter as well as an active shield. The two neutrino double beta decay signals (2v$\beta$) are background in the $Q_{\beta\beta}$ (3 MeV) region. The good energy resolution is crucial to reduce the 2v$\beta$ backgrounds. Neutrino mass sensitivity depends on the energy resolution [4]. The energy resolution, better than 7% in FWHM at the $Q_{\beta\beta}$ (3 MeV) sum energy region, is required. MOON will have large photomultiplier (PMT) coverage to achieve better photon collection efficiency.

3. MOON-1 detector
A prototype MOON detector (MOON-1 detector) was developed to study the energy and position resolutions and the BG rejection capability. As the first step (MOON Phase-1A), use was made of 142 g $^{100}$Mo foils, which was used for ELEGANT-V. We plan to use clean $^{100}$Mo foils of the order of 0.5 kg in near future [5]. 2v$\beta$ is expected to be 3.5 decays/year in the 2.7-3.2 MeV energy windows.

The MOON 1A consists of 6 plastic scintillators, each 1 cm thick and 53 cm by 53 cm and 3 layers of enriched $^{100}$Mo foils (94.5% enrichment), which are divided into four section as shown in figure 1. Each section consists of 2 foils, each with 20 mg/cm$^2$ thick and 18 cm by 18 cm in the area. The $^{100}$Mo foils are interleaved between two plastic scintillators and are supported by the aluminized Mylar films. The film suppresses the cross talk between the plastic scintillators. In order to have better coverage, 56 PMTs are attached to the four sides of the plastic scintillator (about 82% surface of four sides is covered). Silicon cookie is used as the optical connection between the PMTs and the plastic scintillators.

Every PMT sees 3 plastic scintillators. The hit layer can be identified by the PMT hit pattern. The measurement using the MOON-1 detector has been carried out at the Oto underground laboratory (1,500 m.w.e.) since April 2005. MOON-1 detector is placed in the shield of the ELEGANT V detector. 14 of the NaI detectors, each with 10.2 cm by 10.2 cm and 101.6 cm long, are placed above and below the MOON-1 detector. The MOON-1 and the NaI detectors are placed in the air-tight box. In order to keep the Rn concentration low, the detector is in air-tight box filled with Rn-free N$_2$ gas. In this box, Rn concentration was 125 mBq/m$^3$ [6].

4. Results and analysis
The data of 11 days (live time 276 hours) are analysed. The relative gain of every PMT is adjusted by using the Compton scattering of $^{22}$Na 1.27 MeV gamma rays. Absolute energy scale is adjusted with the NaI detectors. The sum of the energy deposits on a plastic scintillator and a NaI detector gives the full energy peak (figure 2). The energy resolution of a plastic scintillator can be obtained from the energy resolution of the reconstructed gamma ray peak and that of the NaI detector. Selecting the energy window of a NaI detector at the 511 keV region, the energy resolution of full energy peak is 47.6±4.3 keV. The energy resolution of the NaI detector for 511 keV gamma rays is measured to be
21.9±2.3 keV. Thus, the energy resolution for a plastic scintillator is 42.3±4.9 keV at the 759 keV region. It is 13.0±1.5% in FWHM.

We select double beta decay events where two beta rays are emitted at opposite sides to give signals at two adjacent plastic scintillators. Two-layers hit events for one $^{100}$Mo foil are analysed. More than 200 keV deposit is required for one layer and more than 500 keV deposit is required for summed deposit on two layers. Hits in the other layers, more than 200 keV deposit, are used as veto events. The sum energy spectrum of the two layer-hit events is shown in figure 3. Here, the NaI detectors are used as veto counters for gamma rays. In this analysis, no event is observed at the $^{100}$Mo Q value (3 MeV) region.

There are remaining events below 2.7 MeV. The origin of the remaining events is due to gamma ray events as the followings: (1) Assuming that gamma rays ($^{40}$K 1.46 MeV, $^{208}$Tl 2.61 MeV) are emitted from the PMTs, the double Compton scattering at the two layers are simulated. The shape of the spectrum is in good agreement with the data. (2) About 50% of events are vetoed by the NaI detectors. The amount of the reduction is consistent with the solid angle of the NaI detectors. (3) The summed energy deposits of the two plastic scintillators and the NaI detectors show the full energy peak for gamma rays ($^{40}$K 1.46 MeV, $^{208}$Tl 2.61 MeV).

![Figure 2](image1.png)  
**Figure 2.** The sum of energy deposits in plastic and NaI causes full energy peak

![Figure 3](image2.png)  
**Figure 3.** The sum energy spectrum of double layer hit

5. **Concluding remarks**

The MOON prototype detector (MOON-1) was constructed. It has been used since April 2005 at the Oto underground laboratory. The energy calibration has been performed using Compton scattering events. The energy resolution for MOON-1 detector is 13.0±1.5% in FWHM at 759 keV region. The two layer hit events were selected to identify the double beta decay events. The main component of the remaining events after the event selection is double Compton scattering events of gamma rays ($^{40}$K 1.46 MeV, $^{208}$Tl 2.61 MeV). At the neutrinoless double beta decay (3 MeV) region, no event is observed for 11 days measurement with 51 g of $^{100}$Mo.

**References**

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