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NEUTRON SHIELDING OPTIMIZATION STUDIES

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Abstract

The IsoDAR sterile-neutrino search calls for a high neutron flux from a 60 MeV proton beam striking a beryllium target, that flood a sleeve of highly-enriched ^{7}Li, the beta-decay of the resulting ^{8}Li giving the desired neutrinos for the very-short-baseline experiment. The target is placed very close to an existing large neutrino detector; all such existing or planned detectors are deep underground, in low-background environments. It is necessary to design a shielding enclosure to prevent neutrons from causing unacceptable activation of the environment. GEANT4 is being used to study neutron attenuation, and optimising the layers of shielding material to minimize thickness. Materials being studied include iron and two new types of concrete developed by Jefferson Laboratory, one very light with shredded plastic aggregate, the other with high quantities of boron. Initial studies indicate that a total shielding thickness of 1.5 meters produces the required attenuation factor, further studies may allow decrease in thickness. Minimising it will reduce the amount of cavity excavation needed to house the target system in confined underground spaces.

ISODAR EXPERIMENT

IsoDAR (Isotopes-Decay-At-Rest) is a novel, high intensity source of electron antineutrinos which aims for searches for physics beyond standard model [1]. The goal is to produce 1.29×10^{23} electron antineutrinos per year with a mean energy of 6.4 MeV. IsoDAR consists of an ion source, a cyclotron accelerating the protons to 60 MeV which impinge on a Be target placed next to a kiloton-scale scintillator detector [2]. The requirement of the accelerator is to deliver 10 mA proton beam at 60 MeV on the target. The solution to provide such a high current is to accelerate 5 mA beam of H_2^+ ions using the DAEDALUS injector cyclotron as a driver. As a results of the inelastic interactions of low energy protons or deuterons with the Be target ^{8}Li isotopes are produced which then decay producing electron antineutrinos. Apart from the ^{8}Li isotopes produced in the target, additional ^{8}Li is produced in the surrounding materials by secondary neutrons. Electron antineutrinos are detected by the inverse-beta decay (IBD) process in a detector and a possible choice for detector is KAMLAND in the Kamioka mine in Japan.

The IsoDAR target (Fig. 1) consists of a hollow cylinder of beryllium with the target proper being a 1.7 cm thick end face of the cylinder. The target thickness is calculated to optimise the production of neutrons and minimise heat deposited in the beryllium. The beam is spread over the 20 cm diameter face of the target by a wobbler magnet that decreases the peak power density deposited on the target. The secondary neutrons produced in the target are moderated in the cooling water before entering the sleeve where they are captured on ^{7}Li to produce ^{8}Li. The purity of the ^{7}Li in the FLiBe sleeve is 99.995%. The sleeve is surrounded by a graphite reflector to reflect the neutrons back into the sleeve.

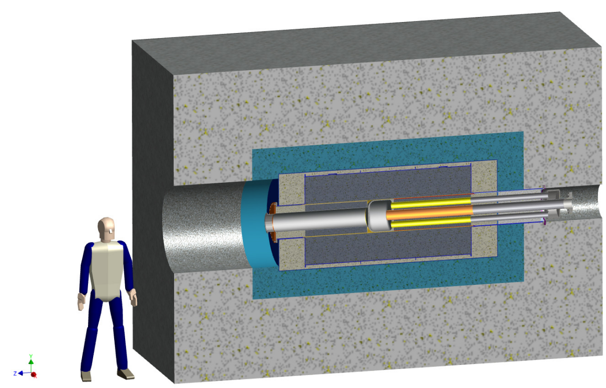

Figure 1: The IsoDAR target system and shielding. The target is a hollow centered cylinder surrounded by the FLiBe sleeve and a graphite reflector and cooled with water. The shielding in the current design consists of steel (shown in blue) and boron rich concrete (grey). A space for wobbler magnets is left in front of the target.

SHIELDING

The proposed site for the IsoDAR target is the KAMLAND control room which has the dimensions 3.5 × 28 × 2.25 m. This space must contain the target assembly and the graphite reflector surrounding the sleeve while the remaining space (≈50 cm) will be used for neutron shielding. Preliminary calculations indicate that the space for neutron shielding will need to be enlarged particularly in the vertical direction. Techniques for rock removal must be discussed as blasting is not allowed.

Our collaborators from KAMLAND and RIKEN gave us valuable guidelines in establishing the requirements of the shielding and radiation protection. In this respect the rock activation due to artificially produced radionuclides must

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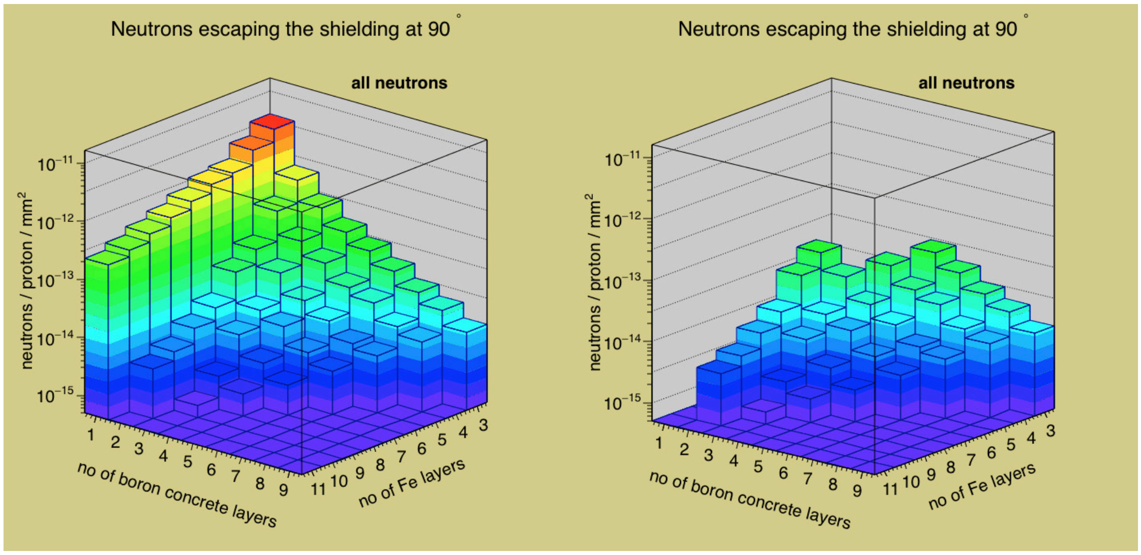

Figure 2: Neutron flux at 90 degrees for various material layers combinations (each layer is 10 cm thick). There are a number of possible material combinations for which the neutron flux is below 10^{-13} n/p/mm^2 (right).

not exceed 0.1 Bq/g. Rock samples collected from various sites in the Kamioka mine were irradiated in the MIT reactor to 10^{18} n/cm^2 and the analysis of the radionuclides produced serves as a useful guide in designing the shielding. As a result of this analysis a rough estimate of a neutron flux below 10^{-13} n/p/mm^2 is required and refined calculations of all the radionuclides produced and their activation will be carried on with the GEANT4 code. Designing a shielding that produces the above neutron flux in the limited available space of the KAMLAND control room is a challenging task and extremely efficient materials to moderate and stop the neutrons must be used. The Jefferson Laboratory (JLab) developed recently new shielding materials. The shielding system they designed consists of three parts: a plastic concrete layer which performs better than other materials for thermalising neutrons, a boron rich concrete layer which absorbs neutrons using less material and boron rich panelling for use in restricted areas. For the Isodar experiment the first two materials are of interest. In concrete the neutrons are thermalised when they strike hydrogen atoms in the water molecules that are trapped during the concrete mixing process. By adding shredded plastic which contains more hydrogen atoms, one can increase the concrete's ability to thermalise neutrons while decreasing its weight. By removing the grit and rocks that are normally found in concrete to make it even lighter, the final product is basically two thirds of the weight of the normal concrete and four times better at thermalising neutrons. Once the neutrons were thermalised they need to be absorbed. For this reason the outer layer is basically Portland concrete without rocks and heavily loaded with boron, as boron has long been used in nuclear plants to absorb neutrons. The boron rich concrete has the same consistency as ordinary concrete.

Simulation studies using various combinations of layer thicknesses of JLab materials show that 100 cm shielding thickness gives a neutron flux above 10^{-13} n/p/mm^2. By adding a layer of 20 cm of steel between the reflector and plastic concrete the neutron flux is decreased below this value. Several layer combinations have a neutron flux below 10^{-13} n/p/mm^2 with the optimum result for 10 cm plastic concrete and 90 cm boron rich concrete ($\approx 2 \times 10^{-14}$ n/p/mm^2). Because the best combination is for the minimum thickness of plastic concrete, further simulation studies were performed using just combinations of steel and boron rich concrete layers to determine the lowest flux one can obtain with a minimal rock removal from the cavern ceiling. Assuming the same total shielding thickness of 120 cm, the results are shown in Fig. 2.

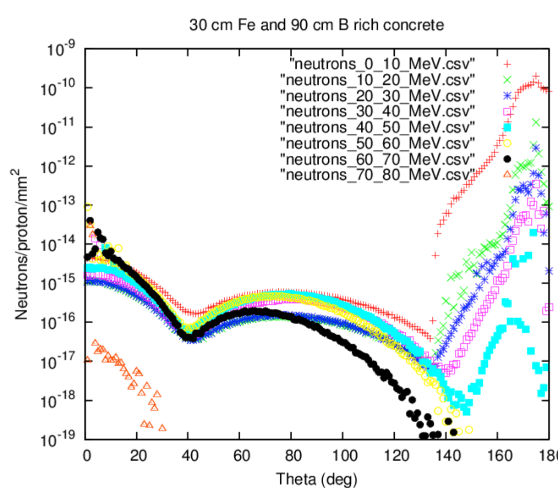

Figure 3: The neutron flux detected on a sphere surrounding the shielding.

As steel poses engineering issues on the reflector and sleeve due to its high density, the combination 30 cm steel and 90 cm boron rich concrete was chosen and the total mass

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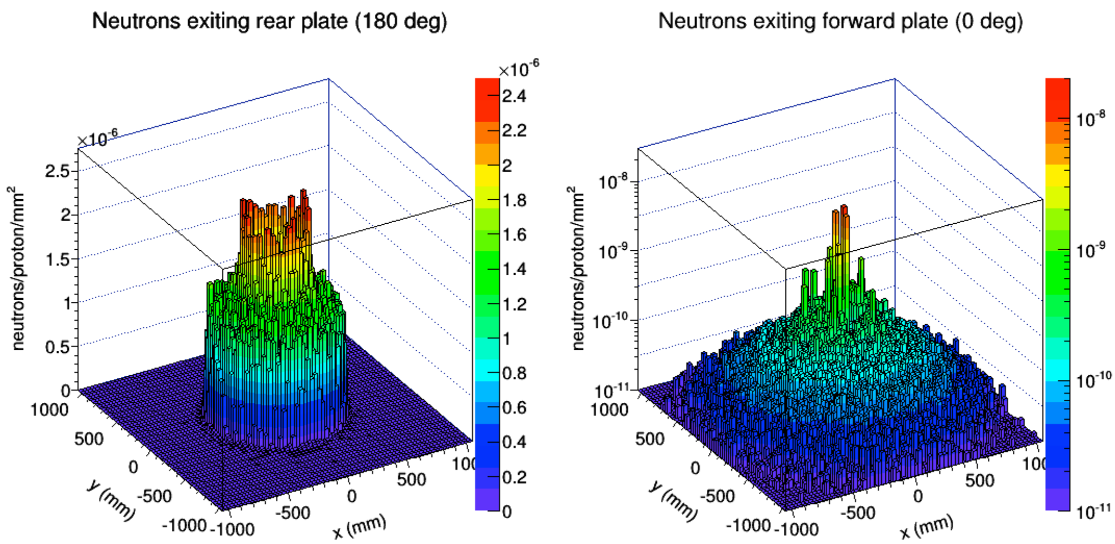

Figure 4: The neutron flux detected on plates placed at the front and at the back of the target .

of the target system and shielding becomes 165,331 kg. The neutron flux for this shielding configuration recorded on a detector sphere of radius 350 cm surrounding the shielding is shown in Fig. 3. The lower flux values at 40 and 140 degrees correspond to the corners of the concrete shielding block and the higher values of flux above 140 degrees correspond to the neutrons escaping into the space left for the wobbler magnets in front of the target. The total neutron flux at 90 degrees at all energies is 1.88×10^{-15} n/p/mm^2.

For a more accurate neutron flux detector plates were placed on the shielding block to record the flux at 0, 90 and 180 degrees for the same shielding configuration.

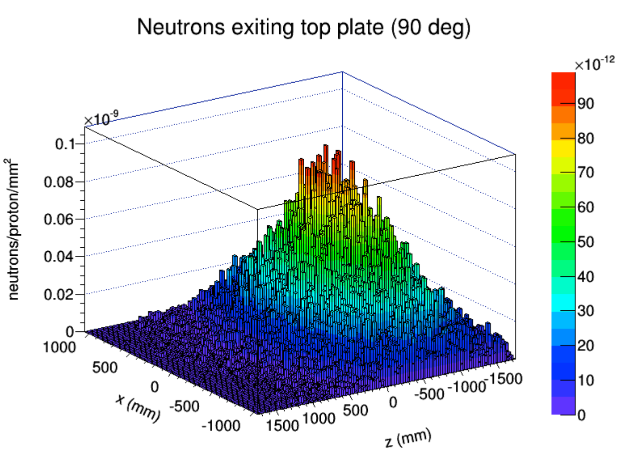

Figure 5: The neutron flux detected on a plate placed on the shielding block.

The neutron flux detected at the front and at the back of the target is shown in Fig. 4. The neutron contamination in the proton beam pipe is 2.4×10^{-6} n/p/mm^2 while the flux in the magnet space is 1.4×10^{-6} n/p/mm^2.

The neutron flux shown in Fig. 5 at 90 degrees is forward biased as most of the neutrons that are backscattered escape in the space left for the wobbler magnets and therefore have no chance to be scattered in the sleeve and detected on the first half of the plate. The total neutron flux is 4×10^{-11} n/p/mm^2.

CONCLUSION

The goal of this study was to design and optimise a shielding for the IsoDAR target which will be placed in a confine space in the KAMLAND mine. Minor rock removal is allowed. The shielding must minimise the neutron flux below a threshold value given by rock sample irradiation analysis. There are several combinations of layers of materials developed at JLab and steel that can achieve a neutron flux below this threshold value. The combination 30 cm steel and 90 cm boron rich concrete was chosen to minimize the total target system weight in the KAMLAND cavern. GEANT4 calculations of the radionuclides produced and total activation in the tunnel is currently being performed.

ACKNOWLEDGMENTS

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