A Study of Neutron Shielding Methods for Experimental Astrophysics

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Abstract

Shielding background radiation sources is an important aspect of research because of its role in low count-rate experiments in nuclear astrophysics. Researching low cost and versatile shielding methods is beneficial in that it may allow experiments detecting cosmic particles and products of nuclear reactions to be carried out without requiring underground facilities; furthermore, the range of statistically significant data obtained from the low-yield facets of an experiment are extended by shielding. The focus of this project is to test the effectiveness of shielding a neutron detector with a $1.55m^3$ tank of water in addition to varying concentrations of borax in the water. Preliminary runs were taken with other shielding materials for eventual comparison with Geant4 simulations of ^{3}He proportional counter neutron detectors. The full water tank was the most effective single shielding material used with a neutron suppression factor of 96.6. The borax solution exhibited only a small improvement over the water in shielding effectiveness with a suppression factor 105.7.

Introduction

It is becoming increasingly important for researchers in the areas of nuclear astrophysics to study low-flux particles and reaction products. Detecting rare particles presents the challenge of having detectors sensitive enough to distinguish incident particles at low intensities; furthermore, it is necessary that the detectors are shielded from extraneous sources, since background activity levels are often comparable to that of the low-flux sources for these experiments. Constructing underground laboratories has been the most common method used to isolate the detectors. While these facilities are generally effective, they are still not completely shielded from weakly interacting and deeply penetrating particles; also, they require extraordinary economic and logistical efforts. It is important to consider alternative means for shielding that are more feasible for lower budget experiments. Neutron shielding is particularly pressing to study because laboratoriescan be subject to a relatively high flux of background neutrons (Miramonti, 2005). Specifically, muons are able to induce neutron background activity even deep underground due to their long penetrating distances (Lammers, 2008). A study of neutron background radiation for underground laboratories describes four mechanisms for neutron production (Wulanderi, Jochum, Rau, & von Feilitzsch, 2004):

1) The Uranium and Thorium present in the concrete and rocks surrounding underground laboratories produce neutrons through fission and (α, n) reactions.
2) Materials in the lab's shielding materials undergo fission reactions, which releases an alpha particle to interact with nearby isotopes through (α, n) reactions.
3) Direct muon spallation with rocks: $\mu +$ Nucleus $\rightarrow \mu + n +$ Nucleus*
4) Muon induced nuclear showers generate hadrons. Neutrons are produced in and further multiply during this cascade.

Neutrons do not possess a charge, so an electrical gradient cannot be used to deflect them. Instead, nuclei with a high affinity for neutrons can be used to absorb them. Hydrogenous material is proficient in thermalizing neutrons in the 1MeV to 15MeV range. Collisions with hydrogen slow the neutrons to thermal energies around 0.025eV (McMillan, 2008). In this range of energies, neutrons have a significantly larger absorption cross section than faster neutrons. It follows that water is a good candidate for serving as a slowing medium as well as a solvent for nuclei with high affinities for neutrons.

The focus of this project is to test the abilities of water and borated water to shield detectors from background neutrons. Preliminary runs taken using alternate shielding materials around the neutron detector were conducted; the results will ultimately be compared with Geant4 simulations of the detector and shielding system. Finally, data taken from a neutron detection experiment carried out in the KN accelerator will be used to exhibit the different sources of background neutron events. The data used for this example is taken from the research of Sascha Falahat, conducted in the Notre Dame Nuclear Structure Lab.

Methods

A vertically-cylindrical, polyethylene water tank was used in the shielding tests. The tank had a radius of .59m and held $1.55m^3$ of water. A 1.07 m PVC pipe was suspended along the center-axis of the tank so that the neutron detector could be housed in the center of the tank. The tank was kept in a room exposed only to environmental background neutrons for all data runs.

The neutron detector used was a ^{3}He proportional counter. The counter, depicted in Figure 1, consists of a cylindrical aluminum tube that contains ^{3}He gas and a high-voltage filament.

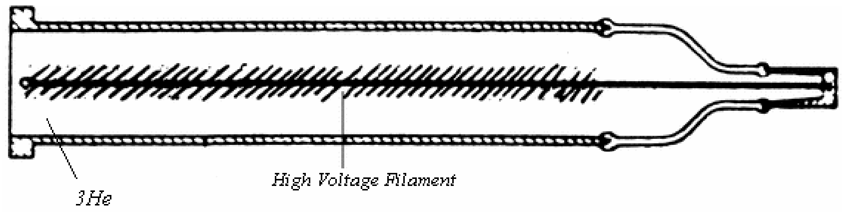

Figure 1. Proportional Counter

When a neutron enters the detector, the products of a $^3He(n,p)\ ^3H$ reaction may cause the helium gas in the detector to ionize; this discharge cascade causes a small fluctuation in the voltage on the filament, which is interpreted as a signal by a pre-amplifier. The number of discharge events created by the proton and triton products is proportional to the number of neutrons incident on the detector, and the size of the signal is related to a statistical process describing the collection of liberated electrons onto the high-voltage filament. Once a signal is produced by the detector it is sent through an amplifier, digitized, and recorded by a computer. The digital signals are plotted with Maestro as a histogram with bins sorted by energy, and the total count of detected neutrons is obtained by integrating over the plot. Though the varying signal sizes are correlated to the energies of incident neutrons, the range of energies seen in the histograms recorded during shielding runs (Fig. 2) is largely the product of variations in the electron cascade as it propagates to the high voltage filament. Each $^3He(n,p)\ ^3H$ reaction releases approximately the same energy in the absorption of a neutron and release of the proton and triton; only small discrepancies arise from the different energies of the incident

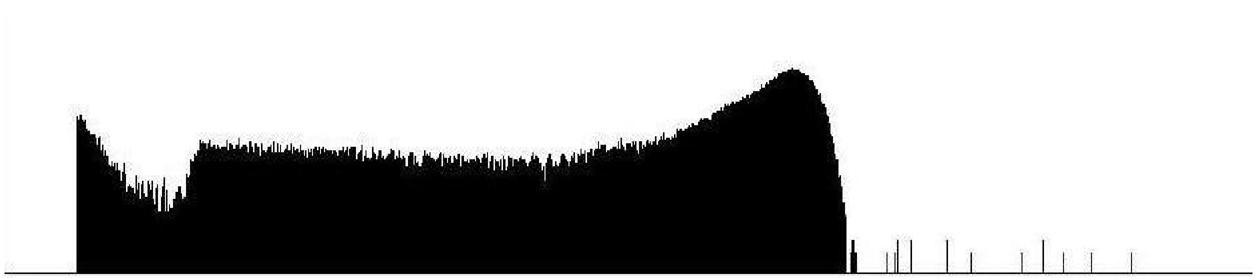

Figure 2. Histogram of neutron count vs. energy (axes omitted)

thermalized neutrons. The count-peak seen at the high energy end of the spectrum in Figure 2 corresponds to the most common variation in voltage on the filament; that is, the peak is produced by the most probable way in which the electrons accumulate on the filament.

Runs with lead and borated polyethylene-board castles used to shield the detector were conducted measuring neutron count rates. These rates will ultimately be compared with Geant4 simulations. The polyethylene-boards used were 1” in thickness, and the lead bricks used were 2” in thickness. Additional measurements of neutron count rates were taken using the PVC pipe, the polyethylene tank as shielding materials, and with a castle of three full borax boxes.

Sascha Falahat’s experiment studying the neutron yield of $Mg(\alpha, n)Si$ reactions for magnesium isotopes utilized ^{3}He proportional counters to detect the neutron products. A neutron detection array was designed to encompass the target chamber of the KN accelerator. It consisted of a polyethylene box depicted in Figure 3 that housed 8 detectors in an inner-ring about the target chamber, and 12 detectors in an outer-ring. The polyethylene material was used to thermalize neutrons in the space between detectors. A 5% boron coating was applied to the outside of the box to shield the detectors from background neutron sources.

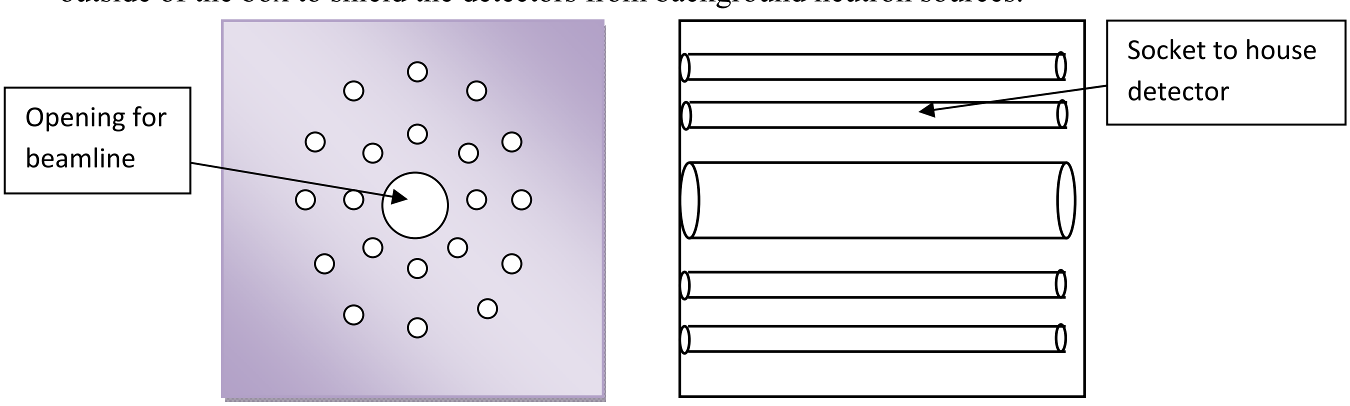

Figure 3. Beamline and detector housing box. A) Front-view with boron coating indicated. B) Side-view cross section.

The aim of the experiment was to obtain the neutron yield of $Mg(\alpha,n)Si$ reactions using ^{24}Mg, ^{25}Mg, and ^{26}Mg isotopes, and varying energies of the α-beam. The yield measured by the detectors must be normalized for beam-induced neutrons and environmental background neutrons. Beam-induced neutrons arise from reactions of the α-particles with carbonous materials in the target plate and with oxygen isotopes bound to the magnesium targets. These neutrons cannot be shielded from the detectors since they are produced within the beamline; rather, the ^{24}Mg target run and runs using blank target backings were used to identify the yield spectrum of beam induced neutrons. ^{24}Mg will not undergo (α,n) reactions, therefore the peaks in the neutron yield for this run result from beam interactions with secondary materials that accumulate during the target making process. The magnesium targets were made by reducing isotopically enriched MgO and evaporating it onto a copper target backing that has a thin nickel lining and a thick gold layer. It is common for oxygen to accumulate on the target during this evaporation process. The neutron yield of the α-beam on a blank target backing was measured. Differences between the yields of the blank backing and ^{24}Mg target runs were most likely the result of α-particles reacting with ^{18}O in the magnesium. Neutrons produced by the blank backing were created by $C(\alpha,n)$ reactions from carbon contamination of the backing materials and beamline components. The natural abundances of these beam-induced neutron sources are minimal; the reactions in which they participate are, however, strong and produce significant background rates. Ultimately, the neutron peaks measured in the background runs can be identified as extraneous detection events for the ^{25}Mg and ^{26}Mg runs.

Results

	Total Neutron Count	Detection Time (s)	Count Rate (1/s)	Error (1/s)	Suppression Factor
No Shielding	84877	95030	0.89315	(+/-) 0.003	1
Lead Castle	81628	110148	0.74107	(+/-) 0.003	1.2
Polyethylene Castle	19083	163316	0.11685	(+/-) 0.001	7.6
PVC Pipe	55307	85983	0.64323	(+/-) 0.003	1.4
Borax-Box Castle	2284	17000	0.13435	(+/-) 0.003	6.6
Tank Background	73231	91869	0.79712	(+/-) 0.003	1
H_2O[a]	8840	10986	0.80461	(+/-) 0.009	1
H_2O[b]	1162	140825	0.0082513	(+/-) 0.0002	96.6
Borax Solution[a]	584	63891	0.0091406	(+/-) 0.0004	87.2
Borax Solution[b]	645	85622	0.0075389	(+/-) 0.0003	105.7

Table 1. Neutron count rate and measured suppression factors. H_2O[a] was conducted with the water tank filled to the bottom of the detector (water height 21"). H_2O[b] was conducted with a 1.55m^3 of water in the tank. The water tank was filled with 1.55m^3 of water for all Borax Solution runs. Borax Solution[a]: 2.15kg borax in water. Borax Solution[b]: 6.45kg borax in water. The suppression factor was calculated as a ratio of the count rate with the shielding material to the background count rate.

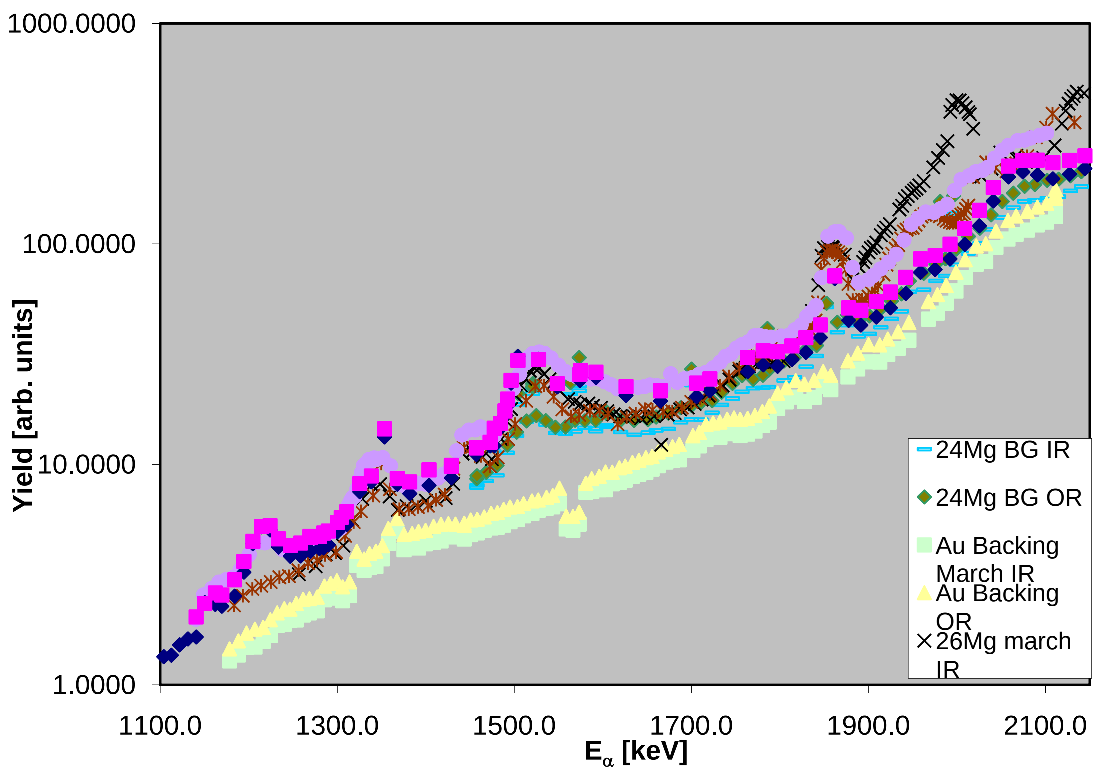

Figure 4. Neutron yield vs. α-beam energy for backing plates and Mg targets. The yield is taken as the total neutrons counted divided by a factor proportional to the total charge incident on the target during the run. Data measured by Sascha Falahat at the University of Notre Dame Nuclear Structure Lab.

Discussion

The 1.55m^3 sheath of water was the most proficient of the shielding materials used, having reduced the neutron count rate by two orders of magnitude from the measured background rate in the water tank (Table 1). Though the 6.45kg borax solution had a larger suppression factor than the full water tank, the shielding effects can be attributed almost entirely to the water solvent. The discrepancy between the shielding effects of the borax castle versus the borax added to the water tank suggests that the way in which the borax was incorporated into the water tank limited the solute's ability to suppress the influx of neutrons. The borax castle constructed out of three borax boxes had a suppression factor of 6.6 without fully enclosing the detector, yet there was little shielding exhibited by the borax solution beyond that of the water. It is likely that this reduction in shielding efficacy was the result of diluting the borax into the water; reducing the density of the borax diminishes the probability that a neutron will encounter a boron nucleus before reaching the detector.

For future shielding tests using borated-water solutions, a motorized pump should be implemented to mix the tank's contents to ensure that the boron solute remains evenly distributed throughout the tank. It would also be valuable to test solutes that have a larger boron concentration and to conduct shielding tests with saturated solutions. This would reduce the mal-effects of diluting the borated material. Future work could also be conducted to assess ways to maximize shielding effectiveness by adjusting the volume of water used given a set amount of boron solute.

The neutron yield spectrum depicted in Figure 4 shows, for all target materials, an exponential decrease in the neutron yield with decreasing α-beam energy. At low energies, the neutron yield arising from primary beam reactions becomes comparable to the yield arising from background neutron activities. The range of energies at which one can statistically subtract out the background neutron count from the yield is limited at this end of the spectrum, and can be extended by isolating the detector array using shielding methods. The neutron yield peaks seen in the ^{24}Mg and Au runs arise from beam-induced secondary reactions. The peaks that are unique to the ^{26}Mg plot are thus identified as resonance peaks for the $Mg(\alpha, n)Si$ reaction.

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References

Lammers, T. (2008). Studies of Muon induced Background at the DoubleChooz Detector. *Diplomarbeit.* Retrieved July 20, 2009, from http://neutrino.desy.de/Diplomarbeit-Thorsten-Lammers.pdf.

McMillan, J.E. (2008). Neutron Shielding for Particle Astrophysics Experiments. arXiv:physics/0510186v1

Miramonti, L. (2005). European underground laboratories: An overview. arXiv:hep-ex/0503054v1

Wulandari, H., Jochum J., Rau W., &von Feilitzsch, F. (2004). Neutron Background Studies for the CRESST Dark Matter Experiment. arXiv:hep-ex/0401032v1