Monte Carlo Simulation of Neutron Background Sources in the Measurement of the $^{12}C(\alpha,\gamma)^{16}O$ Reaction Rate*

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1. Abstract

The $^{12}C(\alpha, \gamma)^{16}O$ reaction rate strongly affects the relative abundances of chemical elements, as well as when core collapse supernovae occur. There have been several attempts to measure the reaction rate, but the Coulomb barrier between the carbon nucleus and the α-particle inhibits direct measurement at stellar energies. In a proposed experiment, a water-filled bubble chamber will be used to measure the reverse reaction rate. This technique will accurately measure the reaction rate closer to stellar energies than previous experiments have accomplished. A potential background source is photoneutrons from the γ-ray beam collimator entering the bubble chamber and generating a false signal. To minimize this effect, a Monte Carlo simulation has been performed to compare the number of photoneutrons created in lead, copper, and aluminum collimators. It was found that 30 cm of copper would be an effective beam collimator by stopping 99.8% of γ-rays and generating no photoneutrons. The simulation also compared the effectiveness of concrete, polyethylene, and water as neutron shields. These simulations show that polyethylene consistently stops the most neutrons at relevant energies. Further simulation will be required to evaluate shielding materials for cosmic ray neutrons, which can also generate false signals.

2. Introduction

The $^{12}C(\alpha, \gamma)^{16}O$ reaction competes with the $^{4}He(2\alpha, \gamma)^{12}C$ reaction in stellar nucleosynthesis during helium burning. While stellar evolution and nucleosynthesis are not critically dependent on the reaction rate of most stellar reactions, the $^{12}C(\alpha, \gamma)^{16}O$ reaction can strongly affect late stage stellar nucleosynthesis. If the reaction rate is too fast, the star will burn the carbon it makes as it is burning helium. Consequently, it will skip the carbon and neon burning stages and go straight to oxygen burning. This affects the relative abundances of elements observed in nature, as well as the effective Chandrasekhar mass [1].

Due to the Coulomb barrier between the carbon nucleus and the α particle, there is uncertainty in the current measurements of the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate at stellar energies. A baseline estimate is given by Caughlan and Fowler[2] but other estimates vary from almost 0 to 5 times this level. In the proposed experiment, a water filled bubble chamber is designed to estimate the $^{12}C(\alpha, \gamma)^{16}O$ reaction rate by measuring the $^{16}O(\gamma,\alpha)^{12}C$ rate. The Duke High Intensity γ-ray Source (HIγS) will generate approximately 10^7 γ/sec with energy near 8.5 MeV [3]. These γ-rays will travel through a beam line, a collimator, and into the bubble chamber.

A γ-ray striking an oxygen nucleus in the bubble chamber can cause it to split into an α particle and a ^{12}C nucleus. Both of these will recoil, which will generate an observable bubble in the superheated water [4]. Counting the number of bubbles generated per unit time can then give the reaction rate of the $^{16}O(\gamma,\alpha)^{12}C$ reaction, which is directly proportional to the $^{12}C(\alpha, \gamma)^{16}O$ reaction.

There are two main advantages to using a water-filled bubble chamber. First, the target density is approximately 1000 times greater than more conventional gas targets. This allows for a much higher counting rate. Second, the bubble chamber is only sensitive to recoiling ions, not the γ-ray beam itself. This significantly reduces the background level.

The main challenge with the experiment is reducing the neutron background level. The sources of neutrons in this experiment are photoneutrons from the collimator and other accelerator hardware, from the bubble chamber entrance window and vessel, and from cosmic ray induced neutrons. Neutrons within the bubble chamber can strike an oxygen or hydrogen nucleus, causing it to recoil. This recoil motion will generate a bubble that is indistinguishable from the desired reaction. While cosmic ray neutrons can only be shielded against, photoneutrons from accelerator hardware and the entrance window can be controlled by careful selection of materials and geometry.

A Monte Carlo simulation using Geant 4 [5] was performed to analyze the photoneutrons created in lead, copper, and aluminum collimators. Concrete, water, and polyethylene were investigated as neutron shielding materials, and their respective neutron absorption rates were compared for neutrons with appropriate energy. Here we propose a setup that could significantly reduce the number of neutrons within the bubble chamber.

3. Physics Validation

Geant 4 can simulate a variety of physical processes. The user chooses those physical processes relevant to the simulation, and disregards everything else in order to save computation time. The electromagnetic physics important to this simulation were the low energy Compton effect, photoelectric effect, ionization, Bremsstrahlung radiation, and e^--e^+ annihilation. The low energy physics lists in Geant 4 include information on atomic shell structure, which is much more important for low energies than high energies. The most important hadronic physics in this simulation is the photonuclear reaction. This is the reaction responsible for the creation of photoneutrons. Other relevant hadronic physics are elastic and inelastic collisions, as well as capture processes for the proton and neutron.

The physical processes used in the simulation were validated by comparing the simulated photonuclear cross section of lead to the experimental results of Berman, et. al. [6]. They measured the photonuclear cross sections of various materials near the Giant Dipole Resonance region and fit the data to a Lorentzian shape

$$\sigma(E) = \frac{\sigma_{\max}}{1 + \frac{\left(E^2 - E_{\max}^2\right)^2}{E^2\Gamma^2}} \tag{1}$$

with fitting parameters σ_{max}, E_{max}, and Γ. The experimental fitting parameters for γ-rays incident on lead, as well as the parameters obtained from the Monte Carlo simulation of the experiment, are shown in Table 1.

The simulated neutron yield was obtained by firing γ-rays at a sample of natural lead with the same shape and size described by Berman, et. al. This yield measurement was converted to a cross section by dividing by several factors. First was the average γ-ray attenuation in the sample, obtained from the analytical expression and coefficient given in the NIST database [7]. Next, the number density of lead atoms was divided out, followed by the thickness of the sample. Finally, the fraction of the total γ-ray beam intensity within the energy range in the neutron yield histogram was divided out. Since the incoming γ-ray beam had a uniform energy distribution from 10-20 MeV, the divisor was a constant 2.082×10^{28} m^{-2}.

The simulated photonuclear cross section is shown in Figure 1, with the Lorentzian fit in black. The red curve is the Lorentzian curve with the experimental parameters given in Table 1. The height and energy of the peaks differ slightly, but they are close enough that the simulation gives an adequate description of the photonuclear effect. The discrepancy is most likely a slight error in the cross sections built into Geant 4. This simulation package was originally designed for high energy physics. While specialized low energy physics has been added, they are not perfect. At 8.5 MeV, the calculated cross section is about 23% too high; therefore, any simulated photoneutron yield in lead should be divided by 1.23 to obtain a more realistic value.

4. Methods

The experiment was modeled in Geant 4 in three stages. First, 10^6 γ-rays were shot along the x-axis towards a collimator with an 11.6 mm diameter hole. The initial y and z coordinates of the γ-rays were chosen from a uniform random distribution from -20 mm to +20 mm. The energy spectrum of the initial γ-rays was Gaussian with mean 8.5 MeV and standard deviation 85 keV. The collimator thickness was varied from 10-30 cm in 10 cm increments, and the three candidate materials were tested at each of these thicknesses. The isotopic compositions of all materials were taken from the NIST database [7]. The initial beam profile was compared to the profile after the collimator to determine how well the collimator stopped γ-rays. The energy spectrum and spatial location of any photoneutrons created in the collimator was also observed.

The second stage of the simulation modeled the neutron attenuation in the shields. In this stage, 10^5 neutrons were shot towards a slab of concrete, polyethylene, or water. The elemental composition of concrete was taken from the NIST database [7]. The thickness of these materials was varied from 10 to 40 cm, in 10 cm increments. The neutron energy spectrum was uniform within the range allowed by the natural lead, copper, and aluminum isotopes. This allowed for a measurement of the neutron attenuation of each of the shields as a function of energy and thickness.

Finally, the γ-ray attenuation of the shields was investigated, and photoneutron generation was studied in the shields and the Pyrex glass currently used as the bubble chamber vessel and entrance window. The thicknesses of the shielding materials were again varied from 10 to 40 cm in 10 cm increments, with the number of γ-rays coming through measured at each thickness. Unfortunately, Geant 4 was unable to simulate photoneutrons from the shielding materials at such low energies. This is because Geant 4 uses experimental cross sections for ^{1}H, ^{2}H, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{12}C, ^{16}O, ^{27}Al, ^{40}Ca, Cu, Sn, Pb, and U to parameterize all of the photonuclear cross sections. For copper, tin, lead, and uranium, the natural isotopic composition is used. Since this experiment operates very near the photonuclear thresholds of most of the isotopes involved, the fourteen cross sections are inadequate to give the correct photonuclear cross sections of elements not in the list. Since lead, copper, and aluminum are all in this list, there was no problem with the collimator simulations in stage 1.

In order to get around this difficulty, the experimental cross sections for ^{2}H [8], ^{10}B [9], ^{13}C [10], ^{17}O [11], ^{18}O [12], ^{25}Mg [13, 14], ^{29}Si [15], and ^{30}Si [16] were found. These isotopes are found in concrete, polyethylene, water, or Pyrex and have neutron binding energies less than 10 MeV. These cross sections were integrated in the range from 6 to11 MeV and weighted by the γ-ray energy distribution. These integrated cross sections were then used to estimate the number of photoneutrons generated by the shielding materials and in Pyrex, as a function of thickness.

5. Results

A: Collimator Analysis

Of all the isotopes present in natural lead, copper, and aluminum, only ^{204}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb have neutron binding energies below 9.5 MeV. Since γ-rays with peak energy between 8-9 MeV will be used, only lead should generate photoneutrons. In addition, the photoneutron energy spectrum should have peaks corresponding to these binding energies at 107 keV, 412 keV, 1.132 MeV, and 1.763 MeV. This was confirmed with the simulation results. Of 773 484 γ-rays entering the collimator material, lead produced 2228 neutrons. Figure 2 shows the neutron energy spectrum. The peak at 107 keV is not visible because the natural abundance of ^{204}Pb is very small and overshadowed by the tail of the 412 keV peak. Figure 3 shows the locations of neutrons ejected from the lead collimator in the direction of the bubble chamber. These neutrons are uniformly distributed, so any neutron created in the collimator has a probability of entering the bubble chamber proportional to the chamber size. Neither copper nor aluminum produced any neutrons.

To determine the effectiveness of the collimator at stopping γ-rays that strike it, another 10^5 γ-rays were shot directly into the material. Figure 4 shows the results of these simulations.

As expected, the γ-ray intensity shows an exponential decay with collimator thickness. Lead is the best at stopping γ-rays, followed by copper. Aluminum is a very poor attenuator, as over 1/3 of the γ-rays striking the material passed through even at 30 cm thickness. Since copper does a good job of attenuating γ-rays, and generates no neutrons, it is a better choice for a collimator material than either lead or aluminum.

B: Shield Analysis

Concrete, water, and polyethylene were all investigated as candidate neutron shields. The neutron attenuation and γ-ray attenuation of the materials was investigated, as well as the number of neutrons created in the shield by γ-rays. Figure 5 compares the neutron attenuation of the materials as a function of neutron energy. At both shield thicknesses, polyethylene is the most effective at stopping neutrons over the entire energy range. A 30 cm thick polyethylene shield will stop most of the neutrons, especially the lower energy ones.

Figure 6 shows the number of neutrons created by one million γ-rays for the shielding materials, as a function of shield length. As stated in the methods section, this figure was not generated with a simulation but directly from experimental cross section measurements. Polyethylene is again the best choice, but it still releases too many neutrons to function with γ-rays passing through it. This problem can be solved by drilling a small hole through the polyethylene for the γ-rays to pass through. While this makes it possible for neutrons to reach the bubble chamber through the same hole, such a neutron is sufficiently rare that it can be ignored.

At 2 mm, Pyrex glass produced about 5 photoneutrons for every 10^6 γ-rays shot into it. Since the beam will contain 10^7 γ/sec, Pyrex glass will create about 50 neutrons in the bubble chamber every second. The dead time of the bubble chamber is much longer than this allows, so a Pyrex entrance window is unacceptable for this experiment. Since silicon and oxygen are the dominant sources of photoneutrons in Pyrex, a pure quartz glass window would also be unacceptable. Copper or aluminum would both be acceptable, since they will not attenuate the beam at low thicknesses, and will generate no photoneutrons.

6. Conclusions

We have studied the effectiveness of lead, copper, and aluminum collimators, as well as concrete, water, and polyethylene neutron shields. In addition, we have calculated the photoneutron yield from Pyrex glass in the bubble chamber. Copper has been found to be the most effective collimator. Since lead produces neutrons when struck with γ-rays, it should not be used as a beam collimator. While neither copper nor aluminum release neutrons, aluminum does a poor job of stopping unwanted γ-rays. Any unwanted γ-rays could strike walls, pipes, or any other equipment in the room and could generate photoneutrons. About 30 cm of copper would stop 99.8% of the γ-rays that strike it.

Of the candidate shielding materials, polyethylene consistently performed the best in this energy regime. A 30 cm thick polyethylene shield would stop most photoneutrons that strike it. To prevent photoneutrons from being released within the shield, a hole should be drilled to allow the γ-rays to pass through. This hole should be the same diameter as the collimator (11.6 mm)

Pyrex glass has been found to be inadequate as a bubble chamber entrance window, since even thin panes of it will generate a significant numbers of neutrons. Aluminum or copper would be good choices, because thin walls would not significantly attenuate the γ-ray beam, and no photoneutrons would be created.

Since neutrons generated by cosmic rays can also reach the detector, further research will be required in order to determine effective shields. These neutrons can have much higher energies than photoneutrons from the collimators or materials in the room; therefore, thicker shielding and different materials may be necessary.

7. Acknowledgements

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Fitting Parameter	Experimental Value	Monte Carlo Value
σ_{max}	602±18.1 mb	619±5.8 mb
E_{max}	13.58±0.41 MeV	13.22±0.016 MeV
Γ	4.20±0.126 MeV	4.25±0.045 MeV

Table 1: Comparison of experimental to simulated fitting parameters

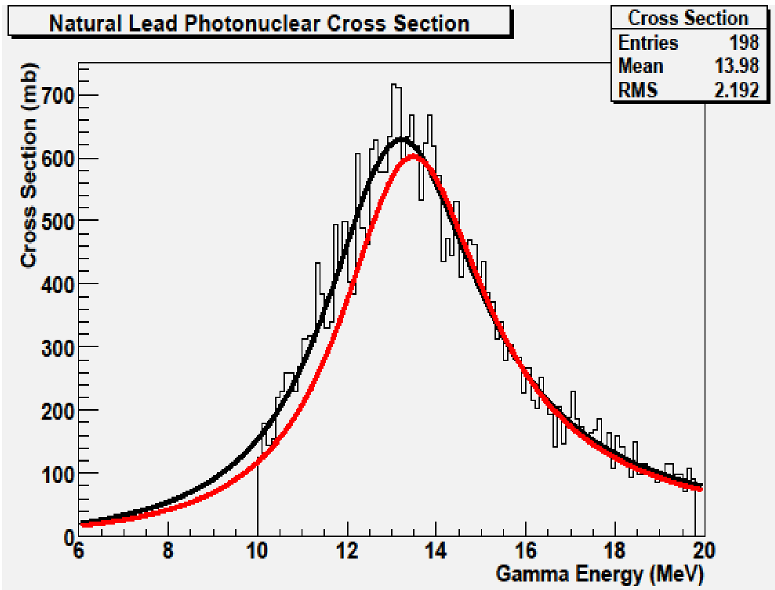

Figure 1: Comparison of experimental and simulated Lorentzian fits of the photo-nuclear cross section in the Giant Dipole Resonance Region. The black curve is a Lorentzian fit from the Monte Carlo data, and the red curve is the experimental fit.

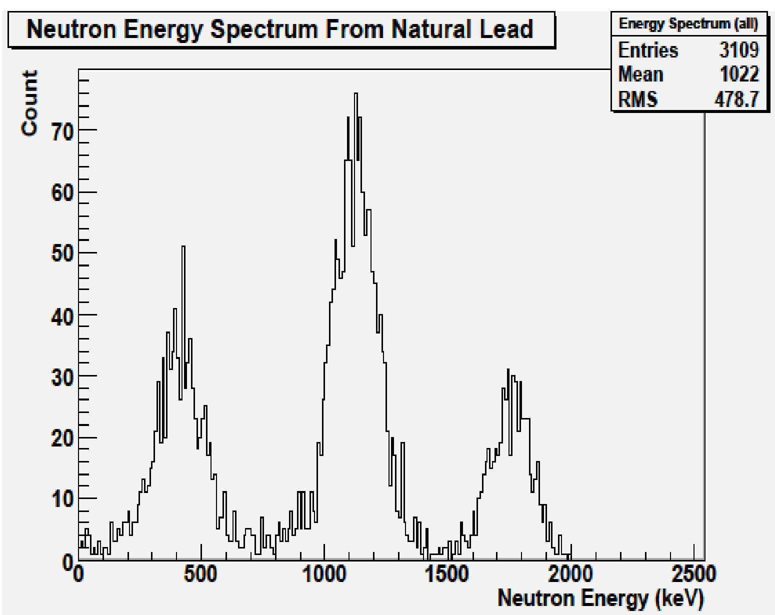

Figure 2: Photoneutron energy spectrum of lead. Incident γ-rays had a Gaussian energy distribution with mean 8.5 MeV and standard deviation of 85 keV.

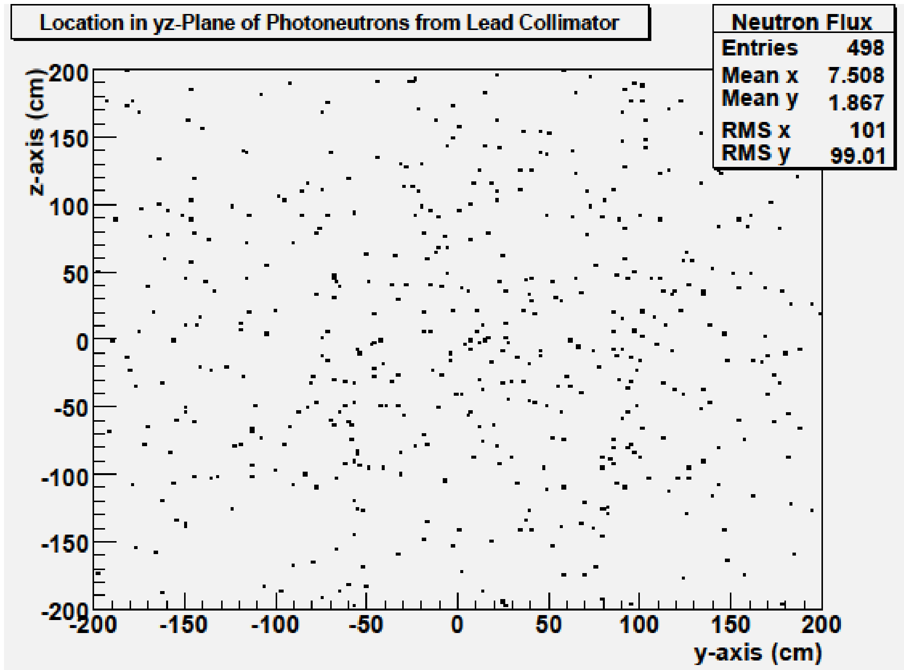

Figure 3: yz-Plane cut of photoneutrons ejected from a lead collimator. The neutrons are very nearly isotropic.

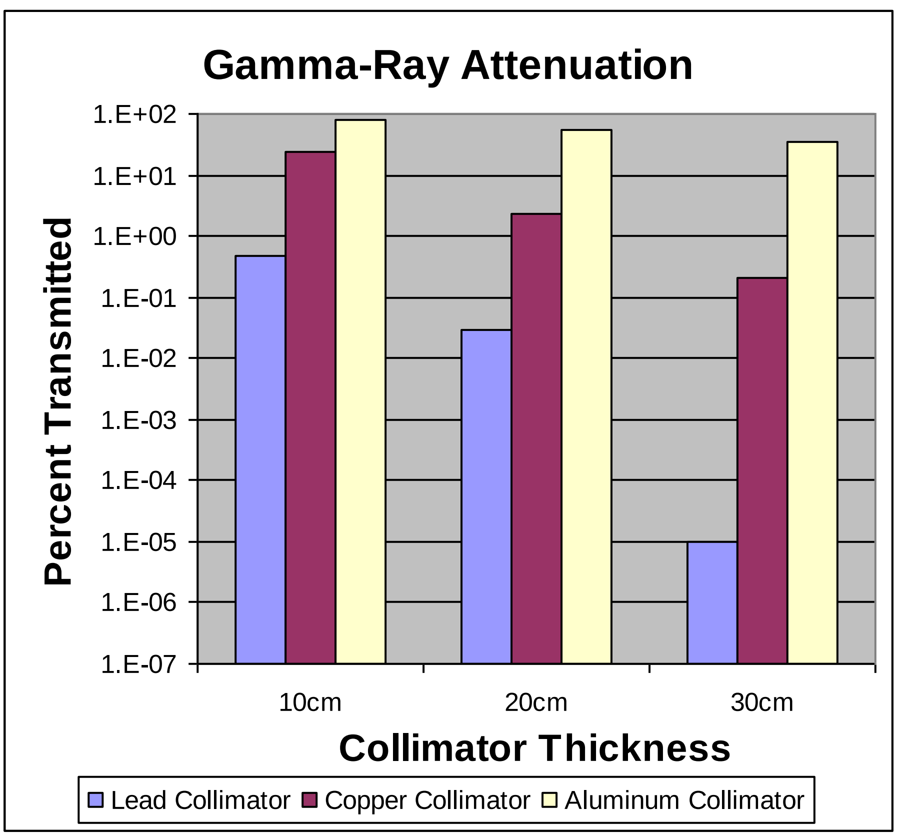

Figure 4: γ-ray attenuation in lead, copper, and aluminum collimators. γ-rays were shot with a Gaussian energy distribution with mean 8.5 MeV and standard deviation 85 keV.

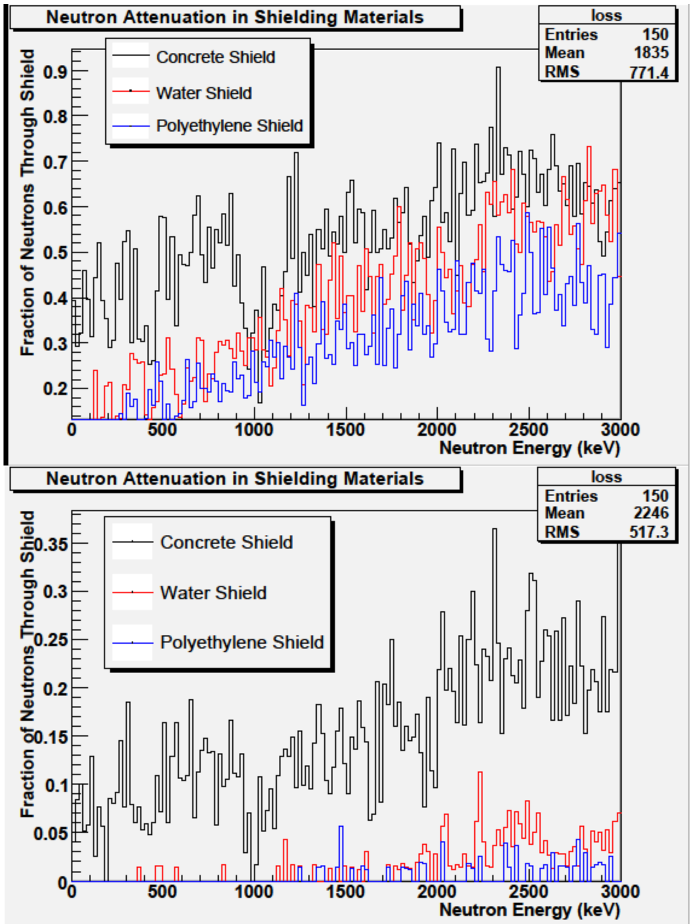

Figure 5: Comparison of neutron attenuation capabilities of concrete, water, and polyethylene. 10 000 γ-rays were shot with a uniform energy distribution from 0-3 MeV. These plots were obtained by dividing the number of outgoing neutrons by the number of incoming neutrons in each bin. Top: 10 cm shield. Bottom: 30 cm Shield.

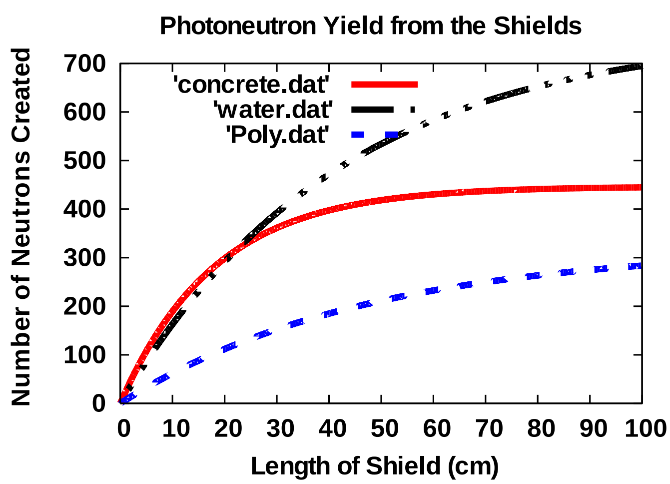

Figure 6: Photoneutron generation in the shields with 10^6 incident γ-rays.