Neutron Shielding for Particle Astrophysics Experiments

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Abstract: Particle astrophysics experiments often require large volume neutron shields which are formed from hydrogenous material. This note reviews some of the available materials in an attempt to find the most cost effective solution. Raw polymer pellets and Water Extended Polyester (WEP) shields are discussed in detail. Suppliers for some materials are given.
Introduction

Neutron shielding is required in current dark matter experiments both on detector systems and on neutron source test and calibration systems. In both applications, large volumes are required, so low cost materials are desirable. The ability to form the shielding material into arbitrary shapes, particularly voids in existing equipment, is important.

Detector systems operated underground must be shielded from environmental neutrons produced primarily by alpha-neutron knock-on reactions as a result of trace uranium and thorium in the rock surrounding the experimental caverns [11]. In this application, since neutron fluxes are low and since the detector systems discriminate against gammas, there is no requirement to minimize \((n-\gamma)\) production in the shield. Low background materials are essential to ensure that the shield does not contribute to the detector background. The ability to incorporate gadolinium, lithium or other elements in a homogeneous manner might be required for future neutrino experiments.

At the surface, experimental systems (and personnel) associated with neutron-beam or neutron-source tests and calibrations of dark matter detectors require neutron shielding. Here attenuation factors need to be as high as possible, so it may be worth using boron loaded material. On some detector systems it may be necessary to minimize \((n-\gamma)\) production in the shield so lithium loading should also be considered as lithium has a high neutron absorption cross-section without gamma production. Where 14MeV neutrons are produced, neutron activation of the shielding materials may become a problem.

The dimensions of shields depend primarily on the neutron attenuation factor required. First order approximations can be obtained from the graphs and tables presented in the standard shielding texts [13, 8, 9, 17], while more detailed simulations are best performed with MCNP [4] as this has more detailed cross-section data and better variance reduction capabilities than any of the alternative montecarlo codes.

Hydrogenous Materials

Fast neutrons, 1 to 15 MeV, are most effectively shielded by materials containing large amounts of hydrogen. The scattering of fast neutrons in collision with hydrogen atoms reduces the energies of the neutrons to epi-thermal and eventually to thermal energies where absorption cross-sections are much higher. The hydrogen may be held as water or as some hydrogenous organic compound. There are many hydrogenous materials which may be useful as neutron shielding. Almost all these materials have a density of \(\approx 1.0\). Table 1 shows a range of hydrogenous materials which have been considered for shielding, together with suppliers and current prices.

Neutron-monitors, used for low energy cosmic ray modulation studies, were some of the earliest particle-astrophysics experiments to require neutron shielding. A review of neutron-monitor designs is given by Hatton [6] and it is interesting to note just how many of the considerations are still relevant to current experiments. The primary requirement was to isolate the experiment from the local background neutron environment. In the early designs 280mm thick paraffin wax shields were used, while in the later designs, extruded polyethylene slabs 75mm thick were used. It was realized that at this thickness the experiment would not be completely isolated from its

| Material                                   | Supplier                        | Price (£/kg) |
|--------------------------------------------|---------------------------------|--------------|
| Water                                      |                                 | 0.00         |
| Paraffin oil                               |                                 | 0.76         |
| Paraffin wax                               |                                 | 1.15         |
| Polypropylene pellets                       | Albis                           | 0.48         |
| Polyethylene slabs                         | John Caunt JC213                | 1.35         |
| Polyethylene slabs                         | Barkston                        | 2.11         |
| Polyethylene slabs                         | IPSL                            | 2.53         |
| Borated polyethylene slabs                 | John Caunt JC201                | 2.13         |
| Boro-silicone                               | John Caunt JC237                | 34.84        |
| Polypropylene slabs                        | IPSL                            | 3.46         |
| Water extended polyester (WEP)             | Scott Bader Crystic 1381PA      | 1.02         |
| WEP + polypropylene pellets                |                                 | 0.70         |
| Resin neutron isolator                     | John Caunt JC243                | 47.54        |
| Neutron isolator                           | John Caunt JC244                | 7.92         |

Table 1: Hydrogenous neutron shielding materials
environment but the choice was a compromise based on the high cost of the extruded material. The expense of extruded or cast slab polymer lies not only in the cost of the raw material, but also in the production of moulds or extrusion dies and the processing. It is still not easy to ensure that slabs are flat and void-free over the large scales required by typical experiments.

**Polymer Pellets**

An alternative approach is to use raw polymer in small pellets, as delivered by the polymer manufacturer, as a neutron shield [16]. Since the requirement is purely for hydrogen solidified as polymer, there is no interest in melting point, average molecular weight or any of the other parameters used by the plastics industry. Even the “high-density” and “low-density” specifications used make no more than a few percent difference to the number of hydrogen atoms per unit volume. Additionally, there appears little to choose between polyethylene and polypropylene pellets. This means that practically any material such as short runs, end-of-batch or similar, may be used to get the best possible price. Care should be taken that it is virgin pure polymer rather than pigmented or re-ground recycled material, primarily to avoid mineral fillers and the risk of contamination by trace radioactive material. Suitable polypropylene pellets have been obtained from Albis (UK) Ltd [1] at a price per kilo three or even four times less than the prices quoted for slab material. Pelleted material has a measured packing fraction of about 0.6, so shields made with this material must be made proportionately thicker than slab material. The main disadvantage of pellets is that they are not load-bearing and some form of containment must be provided.

A system has been developed for NAIAD in which the lead and copper shielding castle is surrounded by an 150mm thick jacket of polypropylene pellets. These pellets are held in woven polypropylene fabric sacks 800mm × 100mm which were filled in-situ. On the outside of the neutron shield is a retaining wall of plywood held in place by steel structural frame. The sacks full of pellets are located between the lead and the retaining wall and the spaces between sacks filled with additional pellets. The pellets are simple to position by pouring and can easily be removed with an industrial vacuum cleaner. This modular construction technique was found simple to assemble and offers the possibility of easy disassembly and re-use of the material on future experiments.

**Water Extended Polyester**

Oliver and Moore [14] recognized that water extended polyester (WEP) was a promising material for neutron shielding since it was essentially 50% water held in a solid form. This material is a liquid thermosetting polyester resin into which water can be incorporated to form a thick emulsion which then hardens to a material similar to a fine-grained plaster. The droplets of the emulsion are in the range 1–5µm and when cured, the aqueous phase remains trapped in these droplets within the rigid polyester matrix. The final material can be easily drilled or machined and will bear substantial loads. A substantial shield for a $^{252}$Cf source fabricated from WEP is described by Veerling [18]. Two currently available commercial versions of WEP have been identified, namely Aropol TM WEP 662P from Ashland Chemical [2] and Crystic 1381PA from Scott-Bader [15].

**Crystic 1381PA**

Experiments have been performed using Crystic 1381PA, a material which will blend with more than 60% water and still harden. The polyester contains carbon, oxygen and carbon, and while the manufacturer’s notes give no details, other polyesters are in the ratio C$_5$H$_4$O$_2$, while the material used in [14] is quoted as C 25.3% H 9.7% and O 65% by weight when cured. The resin also contains an emulsifying agent, [14] mentions cobalt octoate and dimethylaniline, so traces of both cobalt and nitrogen may be expected. The curing catalyst is primarily methylethyl ketone peroxide, a powerful and extremely unpleasant oxidising agent.

The uncured material contains a high proportion of styrene monomer which has a pungent aromatic odour and consequently the mixing and preparation of WEP must be done in a well ventilated building, or preferably outdoors during fine weather. The styrene is fully polymerized during curing and the resulting material has no residual odour. During curing, considerable heat is evolved and consequently it cannot be cast in thicknesses greater than about 100mm. Exceeding this will cause loss of water and in extreme cases, the polyester will begin to degrade and even char.

The resin, as supplied, must be blended with water using a high-shear blender. On an experimental scale, any domestic blender capable of making mayonnaise can be used, on a medium scale
Colemanite, hydrated calcium borate hydroxide $\text{CaB}_3\text{O}_4(\text{OH})_3 \cdot \text{H}_2\text{O}$  
Bainbridge £1.07/kg

Lithium carbonate, presumably fairly pure (flux grade) $\text{Li}_2\text{CO}_3$  
Bainbridge £9.08/kg

Petalite, lithium aluminium silicate $\text{Li}_2\text{OAl}_2\text{O}_7\cdot\text{SiO}_2$  
Bainbridge £0.96/kg

Borax (domestic), hydrated sodium borate $\text{Na}_2\text{B}_4\text{O}_7 \cdot 10\text{H}_2\text{O}$  
Boots £1.63/kg

Table 2: Inorganic neutron capture materials

| Material | Supplier | Price (£/kg) |
|----------|----------|--------------|
| Colemanite | Bainbridge | 1.07 |
| Lithium carbonate | Bainbridge | 9.08 |
| Petalite | Bainbridge | 0.96 |
| Borax | Boots | 1.63 |

Table 2: Inorganic neutron capture materials

an industrial blender would work, while a DOE study \[5\] describes systems capable of producing more than one tonne per day. When the water has been satisfactorily blended, the curing catalyst is added and thoroughly dispersed in the material. The resin emulsion can then be poured into moulds and allowed to set. This happens in about 15 minutes if the specified ratios are used. Cleaning the blender and containers is not difficult but must be done well before the material begins to harden. The costs quoted in table 1 are the raw material costs without any consideration of the expenses of labour or mould production.

An experiment was performed in which Crystic 1381PA was mixed with polypropylene pellets, in order to avoid the packing fraction problem encountered when only pellets are used. The result was a solid concrete-like composite material in which the aggregate was polypropylene pellets. While little care was taken in the production, the result contained very few entrapped air bubbles. This composite is clearly considerably cheaper to produce than pure WEP. It would make an attractive material for use where sacks of pellets are not feasible or where a low cost load bearing shielding material is required.

No experiments have yet been performed on the shielding properties of Crystic 1381PA, though the original work of Oliver and Moore \[14\] gives some measurements. These and considerations of the constituents of WEP suggest that its neutron shielding capabilities will be similar to those of PMMA (Lucite, Perspex).

WEP can easily be blended with inorganic salts or oxides to provide loaded hydrogenous shielding. These inorganic materials can either be inert powders or dissolved in the water phase. It is not thought that inorganics will affect the hardening or emulsifying properties of the resin, provided that strong reducing agents are avoided. Oliver and Moore \[14\] performed experiments with dissolved sodium metaborate and boric acid which had no effect on hardening. They also claim that the emulsion was sufficiently stiff to withstand the incorporation of lead shavings without settling. Recent work commissioned by the DOE \[5\], in which WEP was successfully used to encapsulate radioactively contaminated sludges and salt solutions, indicates that inorganic materials can be blended and that the expected lifetimes of the resulting resins are high.

For neutron shielding, the materials most used would be compounds of Boron and Lithium, both of which have large capture cross-sections at thermal energies. Clearly, for shielding applications, there is little requirement for chemical purity, so domestic materials or finely powdered minerals intended for ceramic glazes may be used with considerable savings in cost. Table 2 shows some materials which have been identified as potential loading materials for WEP neutron shields.

Disclaimer

The suppliers mentioned are primarily British while the prices quoted are those of 2002/3. The lists are in no sense exhaustive.
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