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Broad spectrum moderators and advanced reflector filters using 208Pb

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Abstract

Cold and thermal neutrons, used in neutrons scattering experiments, are produced at nuclear reactors and spallation sources. Neutrons are cooled to thermal or cold temperatures in thermal and cold moderators, respectively. The present study shows that it is possible to exploit the poor thermalizing property of ^{208}Pb to produce a direct bispectral moderator, i.e., a moderator which provides both thermal and cold neutrons from the same position. Furthermore, it is shown that the temperature of the heavy element does not play a vital role for the emitted neutron spectra. Different applications of ^{208}Pb in target-moderator-reflector systems are proposed for generation of higher neutron fluxes and low cost bispectral neutron sources.

Keywords: Spallation, Neutron, Moderators, Lead

Use of ^{208}Pb for Direct Bispectral Moderators

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1. Introduction

In neutron scattering experiments cold and thermal neutrons are used for a wide range of applications. In some of these experiments the main limitation, apart from intensity, is the wavelength range of neutrons which the neutron moderator and extraction system can deliver to a sample. The wavelength spectrum of interest often extends beyond the spectrum of a single temperature Maxwellian distribution. For this reason the possibility of bispectral extraction has been considered for neutron scattering instruments, e.g. at the European Spallation Source, see [1]. A simple method for bispectral extraction is pointing an extraction instrument (a neutron guide) at a thermal moderator positioned next to a cold moderator. Then by placing a neutron super-mirror in front of the neutron guide, cold neutrons from the cold moderator are reflected into the guide, while the thermal neutrons from the thermal moderator are transmitted through the mirror and into the guide [2], some examples of this are found in [1, 3, 4]. However, at high intensity sources the high radiation environment might pose a risk for a mechanical component, such as a mirror. In case of a mirror failure a bispectral instrument will lose its entire cold neutron spectrum, which to most experiments is considered the most valuable part. This motivates an interest in moderators which emit neutrons of several spectral temperatures (or broad-spectra) from the same position and in the same direction. Such moderator systems, however, are difficult to design. Previously, in [5], a com-

posite moderator has been suggested. The composite moderator exploits that neutrons from a thermal moderator can shine through a cold moderator (given that the cold moderator is sufficiently thin), which enables instruments to see both thermal neutrons and cold neutrons simultaneously. This leads to a flux reduction compared to a dedicated cold or thermal moderator, as the composite moderator divides the intensity of the thermal spectrum into a cold and a thermal spectrum.

The present study takes a different approach to the concept of moderation. By exploiting ^{208}Pb's poor ability to moderate and low neutron absorption cross section, it is possible to design a direct bispectral moderator, which combines thermal and cold neutron fluxes from conventional thermal and cold moderators. The heavy material will in this case emit both thermal and cold neutrons.

As this type of bispectral moderator requires the presence of nearby moderators, it can easily be used in conjunction with bispectral extraction via mirrors, providing the maximal cold intensity from the cold moderator. The advantage of such a design over bispectral extraction using a mirror from conventional cold and thermal moderators, is the limited consequences if the mirror fails, as cold neutrons can still be extracted directly from the lead bispectral moderator. However, a disadvantage of a lead bispectral moderator is the reduced thermal neutron flux compared to a dedicated thermal moderator.

2. Moderation in Lead

^{208}Pb is a double magic nuclide with a very low neutron absorption cross section, even lower than that of beryllium, carbon and deuterium. Lead is common in nature, where it is found in two forms, natural lead, with 52.3% ^{208}Pb, and radiogenic lead, where the isotope composition strongly depend on the uranium and thorium content of the ore it is extracted from. According to [6] natural lead can be enriched to 99.0% ^{208}Pb in gas centrifuges for an estimated price of 1000-2000 USD/kg or at a much lower price be extracted from ancient thorium ore, with 85-93% ^{208}Pb depending on the ore quality.

This study is focused on ^{208}Pb, due to its exceptionally low neutron absorption cross section (thermal neutron capture: $\sigma_a < 1$ mbarn). It should be mentioned that similar results could be obtained using natural lead ($\sigma_a = 0.171$ barn) or bismuth ($\sigma_a = 0.034$ barn), but with a reduction in flux due to increased absorption and possibly some changes for cold neutrons in cold materials (Figure 4), from differences in vibrational modes and material structure ($S_{\alpha,\beta}$).

In an elastic collision between a neutron and a lead nucleus, where no energy is transferred in the the center of mass system, there is also almost no energy transfer in the laboratory system, due to the very high mass of lead nucleus compared to the neutron. For this reason lead is only weakly thermalizing. More precisely, the maximum velocity of the neutron after a collision is $\bar{u}_n = 2\bar{v}_{cm} - \bar{v}_n$, where $\bar{v}_n$ is the incoming neutrons velocity and $\bar{v}_{cm}$ is the center of mass velocity. From this it follows that the energy transfer in a head on collision between a neutron and the lead nucleus is given by:

$$U_n = \left(\frac{m_{Pb} - m_n}{m_{Pb} + m_n}\right)^2 E_n + \frac{4 m_{Pb} m_n}{(m_{Pb} + m_n)^2} E_{Pb} + \frac{4(m_{Pb} - m_n)\sqrt{m_n m_{Pb}}}{(m_{Pb} + m_n)^2}\sqrt{E_n E_{Pb}} \tag{1}$$

This formula can be Taylor expanded in $x = \frac{m_n}{m_{Pb}}$ to give:

$$U_n \approx E_n + 4\sqrt{x}\sqrt{E_n E_{Pb}} + 4x(E_{pb} - E_n) \tag{2}$$

From equation (2) we find that a neutron colliding with a ten times more energetic Pb nucleus will at maximum gain approximately a factor two in energy. This is confirmed in Figure 1, showing simulations of a 1 meV (9.05 Å) neutron colliding with different thermal materials. The figure shows that a single collision on water or beryllium brings the neutrons spectrum closer to the Maxwellian distribution than a single scatter on lead.

3. Direct bispectral moderator

Given that lead does not thermalize neutrons in a few collisions, one would expect an ambient temperature piece of lead positioned next to a cold moderator
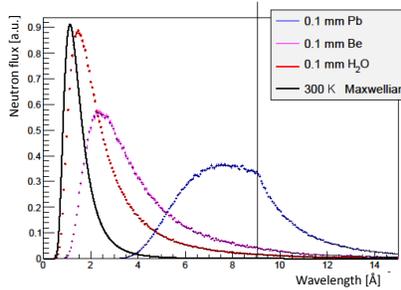
Figure 1: MCNPX [7] have been used to simulate elastic scattering of 1 meV neutrons (vertical black line at 9.05 Å) on 0.1 mm pearls of different materials at 300 K. A 300 K thermal Maxwellian distribution is shown in black. The small size of the scattering media, ensures that most neutrons have only been scattered once (except in water where a few percent of the neutrons scattered twice).

to scatter some of the cold neutrons from the cold moderator into a 4π solid angle without thermalizing, resulting in the thermal lead piece emitting a "cold" spectrum. The lead piece should be properly dimensioned, such that it is large enough for most neutrons to scatter, yet small enough that the neutrons do not thermalize.
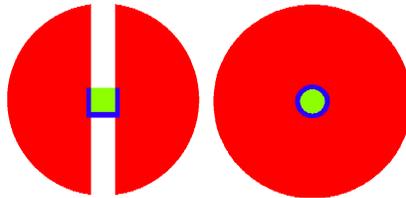

Figure 2: Vertical (left) and horizontal (right) cross sections of the MCNPX test model. The test material of interest is filled in a cylinder of 5 cm × 5 cm (green). It is surrounded, on all sides except the top side, by a 1 cm layer of 22 K solid methane moderator (blue). The moderator system is surrounded by a 20 cm radius sphere of 300 K beryllium (red). The sphere is irradiated isotropically with 1 MeV neutrons. The beryllium sphere has a 2.5 cm radius tube going through it, which enables a direct view of the test material.

One possible configuration is to place moderators on all sides of the lead piece except the side from which the lead is viewed. Such a configuration is simulated in the geometry shown in Figure 2, where different test materials have been placed in a 5 cm tall cylinder of 2.5 cm radius, surrounded by a 1 cm thick cold moderator of solid methane at 22 K, on all sides except the top side. The solid methane is surrounded by a 20 cm radius sphere of beryllium.

The sphere has a 2.5 cm radius tube going through it enabling a direct view of the test material. The beryllium sphere is irradiated isotropically with 1 MeV neutrons. This geometry enables thermal neutrons from the beryllium to enter the test-cylinder from the top, and cold neutrons can enter the test cylinder directly from the cold methane moderator.

Simulated neutron fluxes are shown in Figure 3 where the inner cylinder is filled with 300 K ^{208}Pb, 20 K liquid para-H_2, 300 K water and 22 K solid methane, respectively. Generic MCNPX $S_{\alpha,\beta}$ scattering models are used for solid methane, beryllium, para-hydrogen and water. $S_{\alpha,\beta}$ for ^{208}Pb have been generated in accordance with [8].

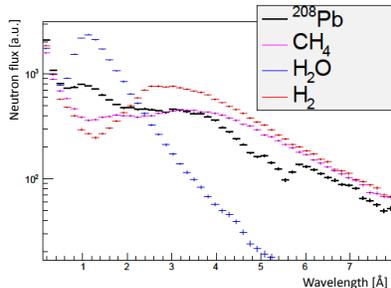Figure 3: MCNPX simulations with 300 K ^{208}Pb, 22 K solid methane, 300 K water and 20 K liquid para-hydrogen in the inner cylinder of Figure 2. Only the neutrons crossing the top surface of the inner cylinder going upwards in a 3° cone are included (a SSW card is written for the top surface of the inner cylinder and only neutrons with maximum of 3° with respect to the surface normal are selected). Lead is not the best moderator in any region, however, it does provide a bispectral spectrum.

As shown in Figure 3 the lead piece does not increase the cold flux when compared to the dedicated cold moderators (para-hydrogen or solid methane), nor does it increase the thermal flux when compared to the dedicated thermal moderator (water). However, it does provide more thermal neutrons than the cold moderators and more cold neutrons than the thermal moderator. This can be used to extract a very broad spectrum of neutrons, both thermal and cold, from the same position on the moderator surface. There is a sharp drop in the cross section for ^{208}Pb around 6 Å for cold or ambient temperature lead [8]. This results in neutrons being emitted directly from the CH_4 without being

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scattered in the lead. It should be mentioned that a similar effect is observed for para-hydrogen, which is also transparent to the cold neutrons from the CH_4 moderator behind it, at wavelengths above 2.3 Å (corresponding to 15.2 meV, which is the energy difference between the H_2 para and ortho spin state).

It should be noted that bispectral extraction using a mirror can still be invoked on a bispectral lead moderator (given that the view of the cold moderator next to the lead is opened up). This would result in full extraction of, in this case, the solid methane cold spectrum. However, when compared to the conventional bispectral extraction case, where water is used as a thermal neutron source, the lead moderator has a lower thermal neutron flux. This does not sound very attractive at first, but one should remember that mirror failure in a conventional bispectral instrument will result in the loss of the entire cold spectrum. In the case of a lead direct bispectral moderator next to a cold moderator, mirror failure will result in the full lead spectrum being retained. This spectrum still contains quite a significant amount of cold neutrons.

4. Other applications

Figure 4 shows simulation results with ^{208}Pb at different temperatures (solid and liquid), in the same geometry as described in Figure 2. The weak spectral temperature dependence observed could prove an advantage in the engineering of a target-moderator-reflector system, where temperatures often vary drastically over short distances and structural compactness is of importance.

Lead is a good choice of target for spallation neutron sources. Because the lead bispectral moderator neutron spectrum only has a small dependence on the lead temperature, a lead piece may be used both as target and cold/thermal neutrons source at the same time. This would allow for a design for a compact spallation neutron source, where the target cooling system act as moderator. Spallation neutrons produced in the lead target are moderated by the target cooling system and will re-enter the lead target at cold or thermal wavelengths, from where they can be extracted for experiments.
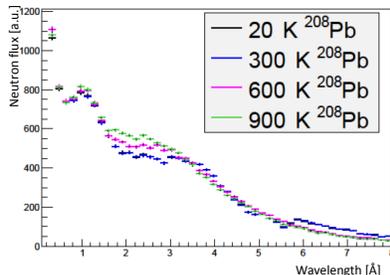
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Figure 4: This figure shows the different spectra obtained with different temperatures of lead in the geometry shown in Figure 2. Note that the melting point of lead is 600.6 K, so liquid lead density is used for the 900 K graph. $S_{\alpha,\beta}$ scattering models [8] were used for 20 K and 300 K. Free gas scattering cross sections were used for 600 K and 900 K. It is clear that the neutron spectrum is not sensitive to the temperature of the lead.

If the target cooling system is positioned around the lead target, covering a large solid angle, this could potentially increase the neutrons fluxes significantly, compared to a conventional facility where the moderator only covers a small solid angle. Furthermore this could provide small scale facilities with an inexpensive and simple bispectral beamline.

5. Conclusion

It have been shown that a direct bispectral moderator can be designed utilizing the poor thermalizing property of ^{208}Pb. Such a direct bispectral moderator can be applied at small scale facilities to produce a simple and inexpensive bispectral neutron source. It is shown that the neutron spectrum is not sensitive to the lead temperature.

The lead bispectral moderator can be used together with a conventional bispectral extraction system, using mirrors. This enables extraction of cold neutrons from the cold moderator. The advantage of such a design is that in the case of mirror failure, the instrument will retain the cold neutron spectrum from the bispectral moderator, while a conventional system would suffer the loss of the entire cold spectrum.

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