Microscopic cross section, the build-up factor, and their uses in the nuclear industry

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The purpose of this paper is to demonstrate the phenomena of neutron attenuation and the build-up factor, along with their possible uses in nuclear shielding. The neutron attenuations of graphite, copper, Lucite and water is measured for various material thicknesses and used to determine the microscopic cross sections of those materials. The build-up factor observed in water and Lucite and its utilization for those two materials in different applications in the nuclear industry is analysed. The neutron attenuation as a function of thickness for four materials was observed and analysed to produce four associated linear functions, relating the net beam intensity decay to the thickness. The absolute value of the slope of those linear graphs were used to obtain the microscopic cross section of each material and was compared to the known values. The microscopic cross sections were determined as 8.616 barns for copper, 4.803 barns for graphite, 186.7 barns for Lucite and 63.29 barns for water and agreed with the theoretically accepted ones within an experimental error, except for the values of water and Lucite, which did not agree, due to the interference of the build-up factor. This concept of the build-up factor was then discussed along with its various uses in the nuclear industry in particular in radiation shielding for water.

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I. INTRODUCTION

Nuclear Energy is one of the main sources for electricity in Canada, as the 19 reactors in Canada provide 13.5 GW of electricity on a yearly basis, which represents 16.5% of Canada's electricity and more than 60% of Ontario's electricity[7]. However Canada spends roughly $161 billion on nuclear safety on a yearly basis, which is roughly 37% of the budget spend on the nuclear industry[8]. The purpose of this study is to examine the build-up factor phenomena observed in the interaction of neutrons with water and Lucite and understand how this phenomena can be used to improve neutron radiation shielding, thus decreasing the amount spend on this safety aspect.

Neutron Attenuation

The study of neutron attenuation and detection and its data analysis is essential for every nuclear engineer as it has multiple nuclear engineering applications and yields information on various material properties, such as the microscopic fission, scattering and absorption cross-section. Neutron attenuation is a term used to describe the interaction of neutrons with matter. There are five different ways for neutrons to interact with matter, inelastic scattering, elastic scattering, radioactive capture, neutron production and fission.

In elastic scattering, which is the first form of neutron and matter interaction, the neutron impacts a nucleus forming a compound nucleus, of which a neutron with the same internal energy as the incident neutron is emitted shortly afterwards. The emitted neutron is slower, as kinetic energy is lost in this process due to the recoil of the impact nucleus. This reaction is denoted by (n, n) and is a very important reaction for neutron "thermalization" in thermal reactors.

The second way of neutron and matter interactions is inelastic scattering. During this process, a neutron influences a nucleus forming a compound nucleus, which then shortly emits a neutron with less energy and then proceeds to decay to its ground state by gamma ray emission. The threshold energy for inelastic scattering is high for nuclei with low atomic numbers and decreases for heavier ones and the reaction is denoted by (n, n').

Radioactive capture, the third form of neutron matter interaction is an absorption process instead of the scattering processes described above. During radioactive capture, a neutron is absorbed into a nucleus forming an excited state compound nucleus, which decays by emitting one or more gamma photons. The reaction is denoted by (n, γ) and the capture results in a transmutation of nuclides, as the mass number of the nuclide increases by one.

Neutron production reactions are also absorption processes. There are two types of neutron production reactions involving neutrons or gamma rays. The neutron–neutron reactions involve only neutrons and are denoted by (n, 2n) or (n, 3n), while gamma–neutron reactions involve both gammas and neutrons and are denoted by (γ, n). Neutrons produced in gamma–neutron reactions are photo–neutrons and occur in reactions containing heavy water or beryllium, due to them containing loosely bound neutrons.

The last form of neutron matter interaction is fission. During fission, a neutron is captured in a nucleus forming a compound nucleus. The absorption of the neutron adds energy to the nucleus. A critical fission energy is required to be added to deform the nucleus and cause it to split apart, however fission may occur naturally, if the binding energy of the last neutron in the compound nucleus is greater than that critical energy. Usually two fission product nuclides, called fission fragments are produced, however fission by high energy neutrons tends to yield more fragments. When fission occurs, two or more neutrons and gamma photons are emitted promptly and the reaction is denoted by (n, f)[1].

Neutron Detection

Neutrons cannot be directly detected, since they have no charge to cause ionization in a detecting medium; therefore, secondary processes must be employed. Fast neutrons can be detected by means of recoil protons following elastic scattering of the neutrons with hydrogen nuclei. Thermal neutrons are usually detected by sensing the nuclear reaction products following neutron capture. One of those reactions, is the reaction of a neutron with boron, producing lithium, an alpha particle and 2.310 or 2.792MeV of energy. This reaction is used to detect thermal neutrons using a detector tube filled with the gas He^3. The alpha particle carries away the bulk of the energy and produces secondary ionizations in the gas. All gas-filled detectors employ a central wire biased with a positive high voltage to collect the resulting electrons. The grounded tube wall attracts the ions. If the bias on the central wire is high enough, a gas-filled detector operates as a Geiger-Mueller tube and all detected ionizing radiations generate a pulse of the same height, whether they be neutrons or gamma rays. Detectors intended to detect neutrons are operated at a lower voltage range, turning the tube into an “ionization chamber” or “proportional counter”, so that there is some relationship between the energy of the ionizing particle and the energy of the pulse. This voltage range also allows the detector to recover more quickly from each pulse, allowing a higher intensity neutron flux to be sensed than is possible in the Geiger voltage region. The resulting current pulses are, however, weak and must be processed through a preamplifier and a linear amplifier.

Beam Intensity

The beam intensity for a material, which is a term that refers to the rate of neutron interactions with matter for that material is proportional to the intensity change as a function of thickness and can be expressed using the following differential equation:

$$-\frac{dI(x)}{dx} = \Sigma_{tot} I(x) \; [1]$$

Where I(x) is the beam intensity of the material as a function of thickness, x is thickness and Σ_{tot} is the total macroscopic cross-section, which is a property dependent on the number density of the sample and the total microscopic cross-section of the material, which is a material property. This differential equation can be solved yielding the following solution:

$$I(x) = I_0 e^{-\Sigma_{tot} x} \; [2]$$

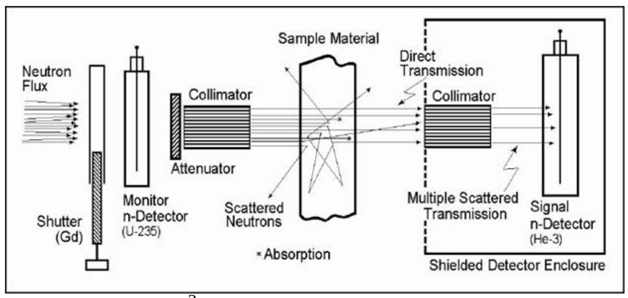
Where I_0 is the initial beam intensity at 0 thickness[2].

Microscopic cross section

The nuclear cross section of a nucleus is used to characterize the probability that a nuclear reaction will occur. The concept of a nuclear cross section can be quantified physically in terms of "characteristic area" where a larger area means a larger probability of interaction. Various cross sections measure the probabilities of neutron absorption, scattering or fission and can be summed up to determine the total cross section of a material.

II. EXPERIMENTAL PROCEDURE

The intensity dependence on material thickness was measured in order to determine the microscopic cross-section for those materials and compare them to the known values. The neutron attenuation of copper, graphite, Lucite and light water at varying thicknesses were measured using the He^3 detector, by firing a neutron beam from the McMaster nuclear reactor towards the four materials, twice at twenty second intervals for each material as per below



shown schematic[3]:

Figure 1: Experiment Schematic used in measuring beam intensity for scattering and absorption events[3]

III. RESULTS

Using the method described above the following results[2] were obtained:

Table 1: Number of neutrons detected for different thickness values for water, Lucite, copper and graphite

Material	Thickness (±0.03mm) (mm)	Trial 1 number of neutrons	Trial 2 number of neutrons	Average number of neutrons
Copper	0	203500 ± 500	202300 ± 400	202900 ± 600
	3.22	163800 ± 400	164400 ± 400	164100 ± 600
	6.44	131200 ± 400	131400 ± 400	131300 ± 500
	9.66	104000 ± 300	103500 ± 300	103800 ± 500
	12.88	82200 ± 290	81800 ± 290	82000 ± 400
	16.1	64030 ± 250	64250 ± 250	64100 ± 400
	19.32	49960 ± 220	49760 ± 220	49800 ± 300
Graphite	0	203500 ± 500	202300 ± 400	202900 ± 600
	10	136700 ± 400	136400 ± 400	136500 ± 500
	20	89700 ± 300	89900 ± 300	89800 ± 400
	30	58080 ± 240	58220 ± 240	58100 ± 300
	40	36930 ± 190	36740 ± 190	36840 ± 270
	50	23490 ± 150	23600 ± 150	23540 ± 220
Lucite	0	203500 ± 500	202300 ± 400	202900 ± 600
	1.8	113500 ± 300	114200 ± 300	113800 ± 500
	3.6	66650 ± 260	66820 ± 260	66700 ± 400
	5.4	36230 ± 190	36220 ± 190	36220 ± 270
	7.2	20990 ± 140	20642 ± 140	20820 ± 200
	9	11400 ± 110	11370 ± 110	11380 ± 150
	10.8	7000 ± 80	7110 ± 80	7050 ± 120
	16.8	1400 ± 40	1490 ± 40	1440 ± 50
	25.4	254 ± 16	277 ± 17	266 ± 23
	32.4	99 ± 10	113 ± 11	106 ± 15
	51.2	34 ± 6	22 ± 5	28 ± 7
	76.6	11 ± 3	13 ± 4	12 ± 5
Light water	0	203500 ± 500	202300 ± 400	202900 ± 600
	1.9	101500 ± 300	102000 ± 300	101700 ± 500
	3.8	49550 ± 220	49320 ± 220	49400 ± 300
	5.7	23640 ± 150	23370 ± 150	23500 ± 220
	10	5930 ± 80	6150 ± 80	6040 ± 110
	15	1290 ± 40	1280 ± 40	1290 ± 50
	20	408 ± 20	414 ± 20	411 ± 29
	25.4	181 ± 13	172 ± 13	177 ± 19
	30	77 ± 8	83 ± 9	80 ± 13
	35	38 ± 6	50 ± 7	44 ± 9
	45.4	23 ± 5	27 ± 5	25 ± 7

The data gathered in Table 1 is plotted as shown:

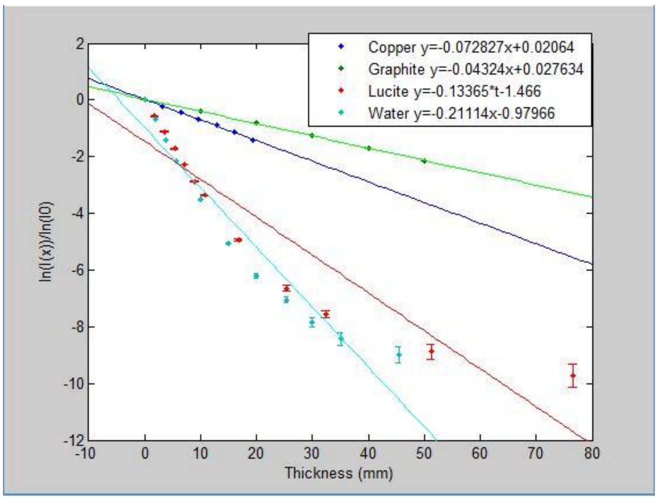


Figure 2: Beam intensity behavior as a function of thickness for the 4 observed materials

As seen above the produced linear relationships have functions of y=-0.072827x+0.02064 for Copper with an R^2 of 0.9992, y=-0.04324x+0.027634 for Graphite with an R^2 of 0.9993, y=-0.13365x-1.466 for Lucite with an R^2 of 0.8869 and y=-0.21114x-0.97966 for water with an R^2 of 0.9381. The R^2 value's reflection can be also clearly seen in the graphs, as the water and Lucite graphs display a less linear behavior than the Copper and Graphite ones.

IV. DISCUSSION

The non-linearity seen in the graphs for water and Lucite in Figure 2 is due to both being highly scattering materials, which causes some neutrons to be reflected back into the beam, adding a so-called build-up factor, and transforming equation [2] to:

$$\boldsymbol{I(x) = I_0[1 + \mu x]e^{-\Sigma_{tot}x}}\ [\mathbf{3}]$$

Where μ is the build-up factor calculated for each material as the ratio of the detector response to the radiation at a point of interest over the detector response to the uncoiled radiation at the same point.

The value of set build-up factor depends on the atomic number of the attenuating material, the energy of the neutrons interacting with set material and the mean free path (distance between the source and the point of interest)[4].

Whereas a plot of the log of intensity versus material thickness should produce a straight line with a slope of $-\Sigma_{tot}$, the impact of the build-up factor will cause the plot to curve upwards with greater thicknesses of scattering material. However, the primary effect is cross section, whereas build-up is a secondary effect.

Using the functions determined and knowing, that the magnitude of the slope of those linear functions is the macroscopic cross section, in inverse millimeter the microscopic cross section can be determined for various materials as 8.616 barns for copper, 4.803 barns for graphite, 186.7 barns for Lucite and 63.29 barns for water.

The values calculated above and presented in Figure 2 prove, that water and Lucite are both much better neutron scattering materials and have a much higher neutron macroscopic and microscopic cross section than copper and graphite. They also confirm the concept discussed earlier of the beam intensity being dependent on the thickness of the material used.

Those values do agree within uncertainties with the known theoretical values of 8.03 barns for copper and 4.84 barns for graphite, but largely disagree with the known theoretical values of 270 barns for Lucite and 103 barns for water[6]. These disagreements can be contributed, to the build-up factor interfering with the slope of the curve. This build-up factor might seem to cause a significant deviation from the accepted value for cross-sections, especially for water and Lucite[2].

This build-up factor is used extensively in the nuclear industry in radiation shielding and other applications. Lead, which is used for alpha, beta, gamma and x-ray shielding, is quite ineffective for blocking neutron radiation, as neutrons are uncharged and can simply pass through dense materials. Materials composed of low atomic number elements are preferable for stopping this type of radiation because they have a higher probability of forming cross-sections that will interact with the neutrons. Hydrogen and hydrogen-based materials are well suited for this task due to their high build-up factor value. Compounds with a high concentration of hydrogen atoms, such as water, form efficient neutron barriers as observed in this lab in addition to being relatively inexpensive shielding substances. However, low-density materials can emit gamma rays when blocking neutrons, meaning that neutron radiation shielding is most effective when it incorporates both high and low atomic number elements. The low-density material can disperse the neutrons through elastic scattering, while the high-density segments block the subsequent gamma rays with inelastic scattering for maximum shielding[5]. Furthermore, Lucite is used for shielding for high-energy beta particles in nuclear medicine for doses used to cure diseases.

V. ERROR ANALYSIS

Throughout this experiment, there were many sources for potential uncertainties. The first source of error is the assumption, that all the neutrons in the neutron beam were thermal neutrons. In addition to this assumption, the assumption that the neutron beam is sufficiently narrow may not always be true. Another gross assumption made about this experiment was the constant value of a cross section. The effects of material thickness on measured cross sections have already been discussed thoroughly. But there are other dependencies on neutron energy such as material temperature, density and 1/v dependence that one should also consider in future studies. In addition to these theoretical uncertainties, there were also uncertainties that occurred due to the equipment used, such as limitations in the use of a He^3 neutron detector, as high-energy neutrons may go through undetected and there is the possibility of reduced count efficiency at high-count rates. There were also sources of uncertainty based on the material used. For example for the water measurements, aluminum casing was required to hold the water in place. Although being thin and having a low cross section, this casing undoubtedly had an effect on the attenuation of neutrons and was not considered in the calculations done.

VI. CONCLUSION

The phenomena of neutron attenuation and the build-up factor were introduced, by determining the microscopic cross section for various materials. The microscopic cross sections were determined as 8.616 barns for copper, 4.803 barns for graphite, 186.7 barns for Lucite and 63.29 barns for water and those values agreed with the theoretically excepted ones within an experimental error, except for the values of water and Lucite, which didn't agree, due to the interference of the build-up factor as discussed. Various theoretical and experimental sources of errors and neutron detection techniques were discussed alongside possible uses of the build-up factor phenomena in neutron radiation shielding, such as the use of water in moderation or Lucite for high energy beta shielding in nuclear medicine.

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a) The experiment was conducted under the supervision of Dr. John Luxat at the McMaster Nuclear Reactor.

b) The article was written under the supervision of Dr. Ayse Turak.

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