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ABSTRACT

The theoretical, experimental and philosophical principles underlying the self-perturbation of a generalized neutron detector on its own spectrum measurements within an experimental medium are examined. It is shown that, in the classical limit, there are two fundamental and physically different aspects of perturbation, namely an "absolute perturbation" which is defined as the change in the neutron transport operator of the system and, more importantly, a "detectable perturbation" which is defined as the difference between the measured detector spectrum and an ideal calculation of the unperturbed system, assuming an otherwise ideal detector. In particular, it is demonstrated that while a detector will always cause an absolute perturbation of the neutron flux by virtue of the detection interactions, this does not necessarily imply that the measured spectrum will show any difference from an ideal calculation of the unperturbed system, irrespective of the detector dimensions. Extension of these arguments through definition of the detector response function establishes that a detectable perturbation will only occur when the interaction processes in the detector subsequently change the ingoing neutron current to the detector surface over that for the equivalent volume of unperturbed medium. Resulting redefinition of the problem of neutron flux perturbation to one of ingoing neutron current perturbation reveals that the neutron-sensitive volume of the detector plays a fundamentally different role to that of the associated outer structure (casing, preamplifier, photomultiplier voids, etc.) Finally, it is shown that, in general, the detectable perturbation may be minimized by selecting a detector with characteristic dimensions small relative to the generalized scattering mean free path of the external medium.

1. INTRODUCTION

Neutron spectrometers have been widely employed for in-situ scalar flux determinations within integral benchmark experimental assemblies.[1-6] Usually, the resulting measurements are compared with corresponding neutron transport calculations for the system. Providing that the overall uncertainties in both the experimental measurements and the methodology of the theoretical calculations are small relative to the uncertainties in the integral nuclear data employed in these calculations, the comparison of experiment and theory provides a direct test of the integrity of this data.[7] One factor which influences the accuracy of the measurements is the perturbation of the neutron field by the neutron spectrometer itself. It might be expected that if this perturbation is large, the neutron transport calculations for the system must include the detector explicitly, a factor which will greatly increase their computational complexity.

Detector perturbation has occasionally received acknowledgement in the literature in that the use of large active spectrometers (e.g., 5 x 5 cm NE 213 scintillation spectrometers) has, in some cases, been rejected in favor of smaller passive techniques such as threshold foils, etc.[8,9] In a recent publication, for example, Sekimoto et al.[10] considered the perturbation of the neutron spectrum in an experimental assembly due to the presence of an NE 213 neutron scintillation spectrometer. Their conclusions included the observation that the perturbing effect due to the neutron-sensitive volume (i.e., the NE 213 organic scintillant) is smaller than that due to associated materials of the spectrometer (e.g., structural case, photomultiplier, etc.).

It is very important, however, to pause here and ask the following questions:

- Just what does the term "perturbation" actually mean when applied to the insertion of a neutron detector into a neutron field?
- Irrespective of its magnitude, would this perturbation necessarily be apparent in the measured spectrum when compared with an ideal calculation of the unperturbed spectrum, assuming an ideal measurement in all other respects?

Examination of these questions will show that there are two fundamental and physically different aspects of detector perturbation and that, under certain conditions, the effect of a finite perturbation is not necessarily detectable in the measured spectrum from an otherwise ideal instrument (i.e., infinite resolution and sensitivity, etc.)

2. WHAT DO WE MEAN BY DETECTOR "PERTURBATION"?

When a detector is introduced, for measurement purposes, into a neutron field, there are two aspects of the resulting perturbation to consider, namely:

- An "absolute perturbation" which may be defined as the change in the neutron transport operator of the system; this simply expresses the change in the neutron field due to the physical presence of the detector and could be obtained, for example, from two transport calculations of the neutron spectrum with and without the detector.
- A "detectable perturbation" which may be defined as the difference between the measured neutron spectrum and an ideal calculation of the unperturbed

neutron spectrum, assuming that, apart from its perturbing effects, the detector is able to perform an ideal measurement.*

By "ideal" calculation, it is meant that no errors or approximations occur due to computational models, cross section data, etc.

The distinction between these two definitions of perturbation is subtle and should be appreciated. It should be noted that in those references on detector perturbation in the literature discussed above, only the phenomenon of absolute perturbation was considered, whereas it is the detectable perturbation which is central to the assessment of the perturbing effects of a neutron spectrometer. In the application of a miniature NE 213 neutron spectrometer to a lithium fluoride integral benchmark experiment,[1] this author has investigated the implications of both these effects.[2] This will be discussed later.

3. A SIMPLE ILLUSTRATION OF "ABSOLUTE" AND "DETECTABLE" PERTURBATIONS

When a spectrometer is placed in an experimental medium, it must, by definition, cause an absolute perturbation of the neutron flux in order to effect a measurement. This is so, since neutrons entering the neutron-sensitive volume of the detector will undergo different interactions with this volume than with the equivalent volume of medium material replaced by the detector. Therefore, the magnitude of the absolute flux perturbation will depend on the difference between the neutronic properties of the detector and the original material replaced by the detector.

*The fact that the detector causes an absolute perturbation of the neutron spectrum does not necessarily preclude it from an otherwise ideal measurement in terms of infinitely fine resolution and sensitivity, etc. This will be discussed later.

However, the fact that the flux has been absolutely perturbed does not necessarily imply that a detectable perturbation has occurred; i.e., the absolute perturbation does not necessarily imply that the spectrum measured by the spectrometer will show any difference from an ideal calculation of the unperturbed spectrum.

As an initial illustration of these arguments, consider Fig. 1. This shows a point neutron source isotropically emitting n neutrons per solid angle per unit time into a vacuum. The vacuum may be considered an infinitely dilute scattering medium. A spectrometer system consisting of two neutron detectors, detector 1 and detector 2, is positioned in the evacuated medium with detector 2 placed behind detector 1 and coaxially with respect to the source. Let detector 1 and 2 subtend solid angles Ω_1 and Ω_2 with respect to the source and let their front face areas be A_1 and A_2, respectively. Assume also that both detectors are 100% efficient so they appear "black" to incident neutrons.

The neutron flux as measured by detector 1 will be

$$\phi_1 = n\ \Omega_1/A_1 \ . \tag{1}$$

Now since an ideal calculation of the flux at the spatial coordinate corresponding to the front face of detector 1 gives exactly the same result, it can be seen, from the definition above, that there is no detectable perturbation at detector 1, irrespective of the size of the latter. Therefore, a perturbation correction to the experimental measurement is not required.

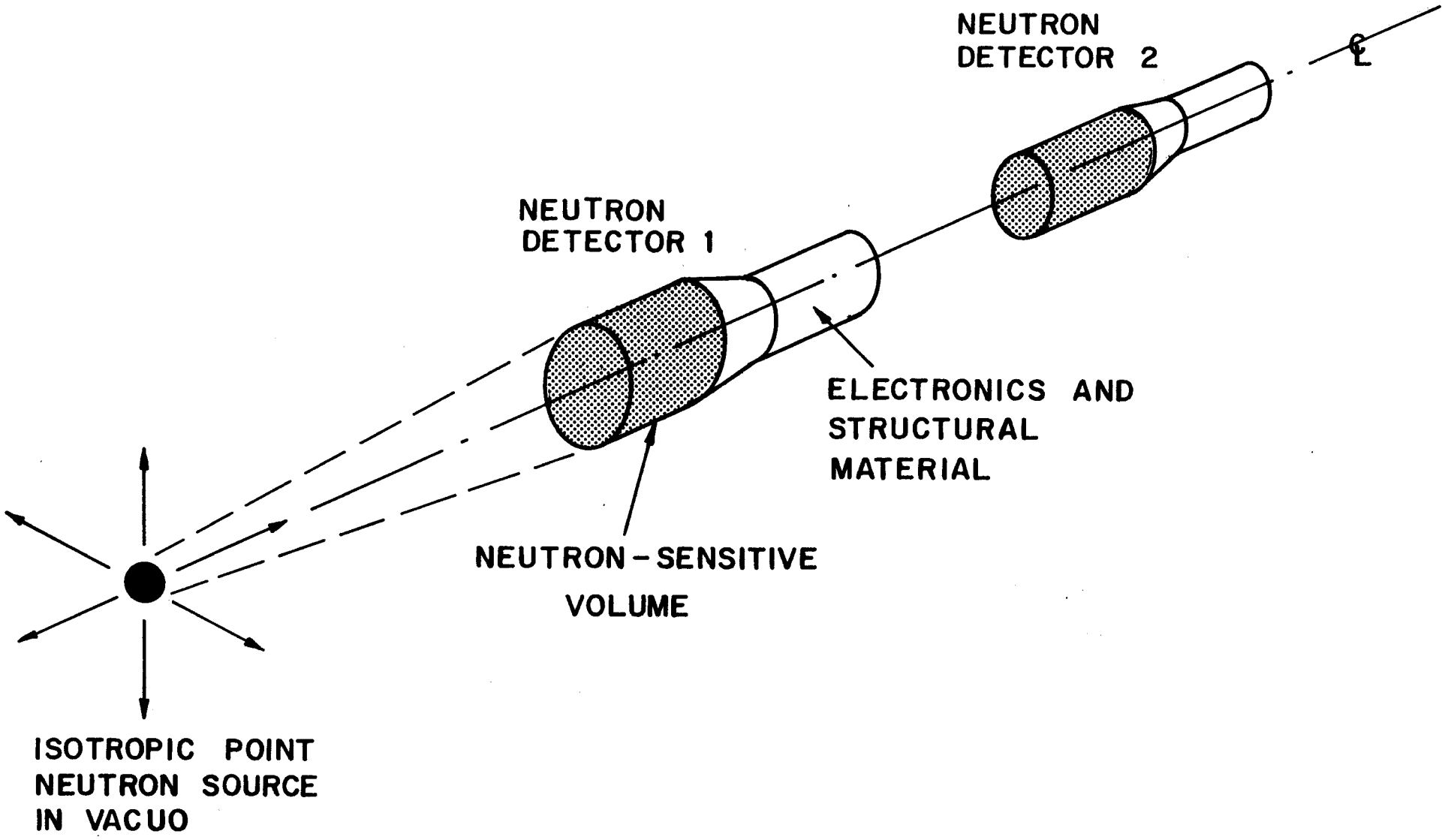

Fig. 1. Illustration of absolute and detectable perturbations. The isotropic neutron source is situated in vacuo and emits n neutrons per solid angle per second. The spectrometer system comprises two neutron detectors, detector 1 and detector 2, both 100% efficient.

Detector 1 has, of course, produced an absolute perturbation of the flux in its vicinity due to the detection process and this absolute perturbation is clearly apparent at detector 2 where the measured flux is now

$$\phi_2 = \frac{n\ (\Omega_2-\Omega_1)\ H(\Omega_2-\Omega_1)}{A_2} \tag{2}$$

where $H(\Omega_2 - \Omega_1)$ is the Heavyside function.

An ideal calculation at detector 2 would predict

$$\phi_2 = n\ \Omega_2/A_2\ . \tag{3}$$

To summarize this example, detector 1 has produced an absolute perturbation in the neutron flux in its vicinity, but the results of its measurement show no effect of this perturbation (i.e., no detectable perturbation) since they are identical to the ideal calculation. The absolute perturbation due to detector 1 is, however, evident at detector 2.

4. ABSOLUTE AND DETECTABLE PERTURBATION IN A PHYSICALLY-REALIZABLE SITUATION

In order to enhance our appreciation of the physical difference between absolute and detectable perturbations, the example in Fig. 1 will now be extended to a real detector in a physical medium. Consider Fig. 2. This shows a neutron detector of arbitrary efficiency comprising a neutron-sensitive volume (e.g., NE 213 organic scintillator, BF_3 gas, etc.) and its associated structure (e.g., outer case, photomultiplier, preamplifier, etc.). The detector is positioned in a neutron scattering medium for purposes of flux determination.

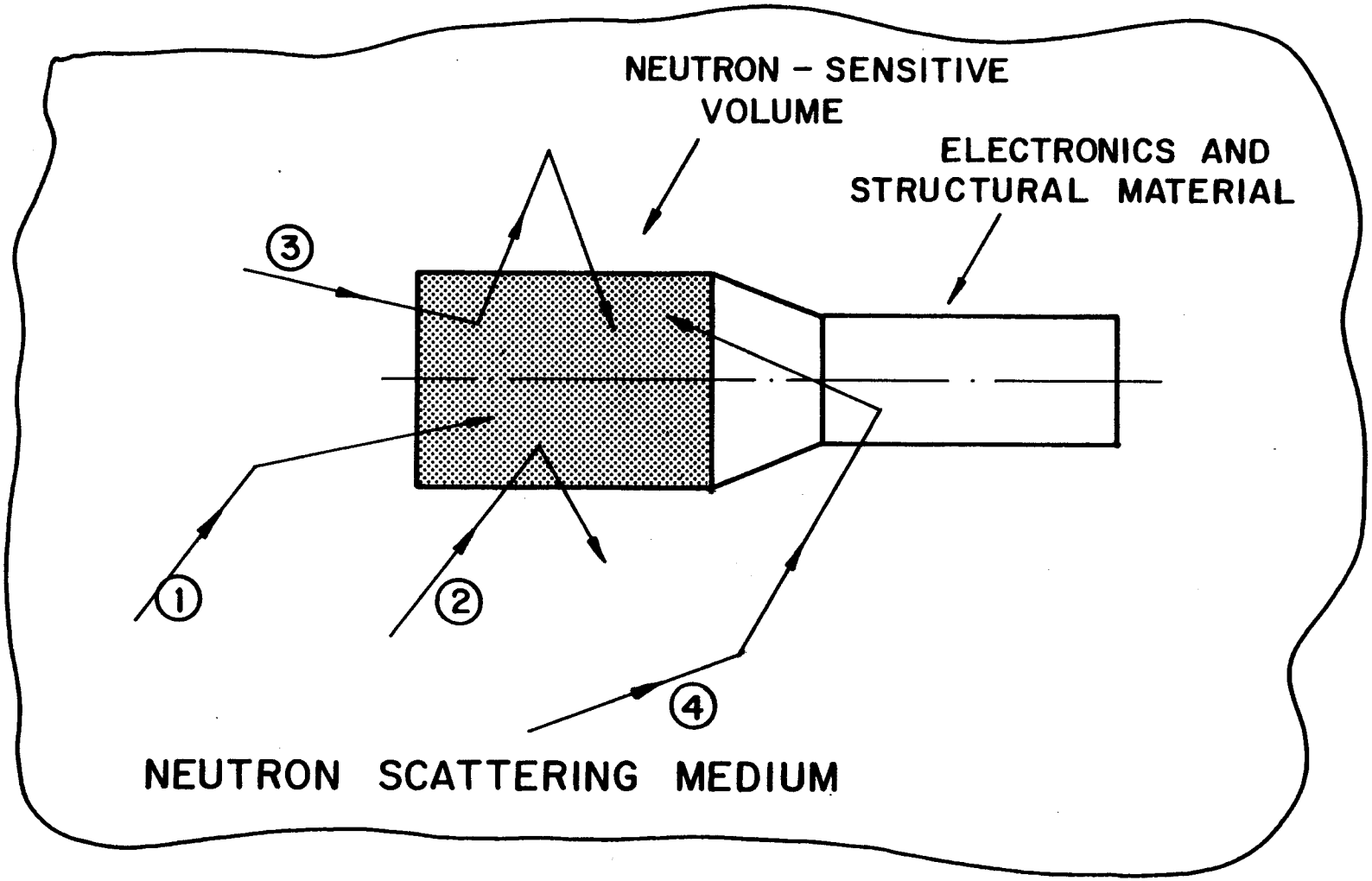

Fig. 2. Neutron interaction processes contributing to the perturbation of a real detector situated in an external neutron scattering medium.

From the considerations above it can be seen that, unless the neutronic properties of the detector are identical to those of the scattering medium in which it is situated, an absolute perturbation of the neutron flux in the system must occur. However, to assess the degree of detectable perturbation of this spectrometer, it is important to appreciate that such detectors provide quantification of the neutron spectrum not from the neutron flux $\phi(\underset{\sim}{r},E)$ in their vicinity, but from the ingoing neutron current at the detector surface.[2,12] This ingoing current may be written

$$C(E) = \int_{-} d\underset{\sim}{s}\cdot\underset{\sim}{J}(\underset{\sim}{r},E) = \int_{-}\int_{4\pi} d\underset{\sim}{s}\cdot\underset{\sim}{\Omega}\ \Phi(\underset{\sim}{r},\underset{\sim}{\Omega},E)\ d\underset{\sim}{\Omega} \tag{4}$$

where $\underset{\sim}{J}(\underset{\sim}{r},E)$ is the neutron current density, $d\underset{\sim}{s}$ is a vector element of the detector surface with direction along the outward normal, $\Phi(\underset{\sim}{r},\underset{\sim}{\Omega},E)$ is the neutron angular flux and the negative sign on the integral denotes that the surface integration is to be carried out only where $d\underset{\sim}{s}\cdot\underset{\sim}{\Omega}$ is negative. By contrast, the surface integral of the scalar flux would be

$$S(E) = \int \phi(\underset{\sim}{r},E)\ d\underset{\sim}{s} = \iint_{4\pi} \Phi(\underset{\sim}{r},\underset{\sim}{\Omega},E)\ d\underset{\sim}{\Omega}\ d\underset{\sim}{s}\ . \tag{5}$$

Extending Eq. (4), the response R(E') of the detector to the ingoing current C(E) can be expressed by the Fredholm integral

$$R(E') = \int_{E}\int_{-}\int_{4\pi} d\underset{\sim}{s}\cdot\underset{\sim}{\Omega}\ \Phi(\underset{\sim}{r},\underset{\sim}{\Omega},E)\ M(\underset{\sim}{r},\underset{\sim}{\Omega},E,E')\ d\underset{\sim}{\Omega}\ dE \tag{6}$$

where $M(\underset{\sim}{r},\underset{\sim}{\Omega},E,E')$ is the detector "response function" and expresses the probability that an incident neutron of energy in the range dE about E will give

rise to a detector response signal dE' about E'.[2] Note that the response function is formally dependent on the incident neutron direction of travel $\underset{\sim}{\Omega}$ and of its coordinate of inward entry $\underset{\sim}{r}$ through the detector surface.

Formally, in order to extract the original neutron spectrum information from the measured response R(E'), the latter must be deconvoluted with the aid of the detector response function. The measured ingoing neutron current spectrum from the detector can, therefore, be written

$$C_d(E) = U\,[R(E')\ ,\ M(\underset{\sim}{r},\underset{\sim}{\Omega},E,E')] \tag{7}$$

where U[,] represents the deconvolution operation. If, for example, the integral in Eq. (6) was to be formulated in matrix notation, then Eq. (7) would represent the multiplication of the matrix R(E') by the inverse of the response function matrix $M^{-1}(\underset{\sim}{r},\underset{\sim}{\Omega},E,E')$.

From Eq. (5), the absolute perturbation of the detector can now be written

$$P_A = S(E) - S^P(E) = \int \phi(\underset{\sim}{r},E)\ d\underset{\sim}{s} - \int \phi^P(\underset{\sim}{r},E)\ d\underset{\sim}{s} \tag{8}$$

where $\phi(\underset{\sim}{r},E)$ is the unperturbed scalar flux where no detector is present and $\phi^P(\underset{\sim}{r},E)$ is the perturbed scalar flux due to the presence of the detector. Clearly $P_A = 0$ and $\phi(\underset{\sim}{r},E) = \phi^P(\underset{\sim}{r},E)$ only when the neutronic properties of the detector are identical to those of the external scattering medium. The detectable perturbation on the other hand can be written

$$P_D = C(E) - C_d(E) \tag{9}$$

where C(E) is the ingoing current from the ideal calculation of the unperturbed system and $C_d(E)$ is the corresponding measured value from the ideal detector. Substituting the expression for the detector response R(E') from Eq. (6) into Eq. (7), enables the deconvoluted detector spectrum to be expressed by

$$C_d(E) = U\left[\int_E dE \left\{\int_{4\pi} d\underset{\sim}{\Omega} \int_- d\underset{\sim}{s}\cdot\underset{\sim}{\Omega}\ \Phi(\underset{\sim}{r},\underset{\sim}{\Omega},E)\right\} M(\underset{\sim}{r},\underset{\sim}{\Omega},E,E')\ ,\ M(\underset{\sim}{r},\underset{\sim}{\Omega},E,E')\right] . \qquad (10)$$

Notice, however, that since the detector has been defined as "ideal" apart from a possible detectable perturbation effect, then both the response function $M(\underset{\sim}{r},\underset{\sim}{\Omega},E,E')$ and the deconvolution process U[,] contain no errors or uncertainties. Thus, the detectable perturbation P_D in Eq. (9) is only non-zero when the ingoing neutron current enclosed within the inner braces in Eq. (10) differs from the value C(E) obtained from the ideal calculation of the unperturbed system.

Therefore, if and only if the detection interactions in the spectrometer subsequently change the ingoing current over that current entering the equivalent volume of unperturbed scattering medium, will there by any detectable perturbation between the measured spectrum and that of an ideal calculation. Note that the fact that the ingoing neutron current will undergo interactions within the spectrometer necessary for the detection process, thereby changing the outgoing current and yielding a perturbed flux $\phi^p(\underset{\sim}{r},E)$ (and, therefore, always causing an absolute perturbation), is irrelevant since this is accounted for in the response function $M(\underset{\sim}{r},\underset{\sim}{\Omega},E,E')$ of the detector (see later). Therefore, the important consideration in experimental measurements is not flux perturbation but rather ingoing neutron current perturbation.

Consider now those processes of detection which may change the ingoing neutron current and, therefore, contribute to a detectable perturbation. In Fig. 1, detector 1 was defined as 100% efficient such that all neutrons entering this detector were completely absorbed. Therefore, although there was an absolute flux perturbation at the detector, the ingoing neutron current was unchanged and no detectable perturbation occurred. In the case of the real detector in the scattering medium in Fig. 2 there are various processes to consider. Neutron number 1 in this figure enters the sensitive volume and is completely absorbed, giving all its energy to the detector response. Neutron number 2 undergoes a scattering interaction in the sensitive volume, gives up a fraction of its energy to the detector response and leaves the detector to be absorbed somewhere in the outside medium. Since both these detection interactions do not affect the ingoing neutron current, there is no detectable perturbation of the measured flux. Neutron number 3 scatters out of the sensitive volume and, as number 2, provides a fractional contribution to the response. However, it re-enters the detector due to a subsequent nearby scattering reaction in the medium, thereby perturbing the ingoing current and directly contributing to a detectable perturbation between the measured spectrum and the ideal calculation.

Neutron number 4 in Fig. 2 presents an interesting situation since it scatters in the outer structure of the detector before being absorbed in the sensitive volume. There is no doubt that this neutron has perturbed the ingoing current to the sensitive volume since the outer structure possesses different neutronic properties to the equivalent volume of medium that it replaces. However, note that unless this neutron subsequently scatters out of the sensitive volume and scatters back in again from the medium, it can be

seen that the ingoing current to the detector as a whole (i.e., sensitive volume plus outer structure) is unchanged. It is important, therefore, to define just what is meant by "detector" when assessing changes in ingoing current.

It should be noted here that scattering events 2, 3 and 4 are really special cases of general secondary neutron production events in which one or more neutrons may be produced, e.g. (n,n), (n,2n), (n,np), etc. In this context, identical considerations apply in that only those secondary neutrons produced in the detector which escape to the outside medium and subsequently scatter back in (or, equivalently, give rise to further secondary neutrons which enter the detector) will contribute to a detectable perturbation.

5. WHAT CONSTITUTES A "DETECTOR"?

For a detector which consists purely of a sensitive volume (e.g., a threshold foil), the definition of the "detecting-portion", for which the ingoing neutron current must remain unchanged for no detectable perturbation, would appear to present no problem. All active spectrometers, however, have some associated structure (see Fig. 2) and the definition of their "detecting-portion" requires consideration of how they are initially calibrated as follows.

It was shown in Eq. (7) above that in order to obtain the required neutron information from a neutron detector, the measured response R(E') must be deconvoluted by means of the detector response function $M(\underset{\sim}{r},\underset{\sim}{\Omega},E,E')$. For a simple integral flux monitor, for example, the response function may merely be a set of energy-dependent efficiency corrections. However, for a spectrometer, the required neutron spectrum must be "unfolded" from the measured response by means of a response function consisting of a complex matrix of

individual response vectors.[2,11,15] These individual energy-dependent responses can be obtained either by numerical Monte Carlo modeling[12] or measured experimentally by way of monoenergetic neutron sources of known intensity.[13] Therefore, provided that the outer structural material of the spectrometer is included in the response function determination, it would appear that a detectable perturbation occurs only for a change in the ingoing current for the whole detector and not just the sensitive volume.

Unfortunately, response functions are invariably determined either from isotropic fluxes, or, in the case of experimental calibrations, from monodirectional monoenergetic fluxes incident on one face of the sensitive volume (usually the front)[1,2], whereas the formal response function $M(\underset{\sim}{r},\underset{\sim}{\Omega},E,E')$ in Eqs. (6) and (7) above is a function of both the direction of travel $\underset{\sim}{\Omega}$ of the incident neutron and the position $\underset{\sim}{r}$ of entry through the detector surface. Therefore, the definition of "detector" applies to those portions of the spectrometer in which neutrons interact from directions equivalent to those in the original response function calibration. In fact, the detection efficiencies per unit incident current flux of homogeneous neutron-sensitive volumes of spherical shape, or of cylindrical shape with diameter and height dimensions in the same order of magnitude range, are virtually independent of $\underset{\sim}{\Omega}$.[2] Therefore, for the vast majority of practical neutron detectors, we may define our "detector" as the sensitive volume plus those portions of the associated structure in which neutrons interact from directions equivalent to those in the original calibration.

If the detector in Fig. 2 was originally calibrated, for example, by exposure to monoenergetic neutron fluxes incident on the front face, then neutrons which enter the sensitive volume following a scattering event in the

associated structure are compensated for in the response if, and only if, they originally entered the structure via the front face of the sensitive volume. It can be seen that neutron number 4 does not obey this constraint and is, therefore, directly capable of changing the ingoing current of the detector and thus contributing to a detectable perturbation.

To summarize this section, it can be seen that there are two aspects in the consideration of contributions to detectable perturbation, namely (1) that due to the neutron-sensitive volume of the spectrometer which causes a detectable perturbation only if the detecting interactions in this volume subsequently change the ingoing neutron current and (2) that due to any associated structures (including voids) which, unless compensated for in the response calibration, directly perturb the initial ingoing current to the sensitive volume.

6. CONCLUSION: THE DEPENDENCE ON THE SCATTERING MEAN FREE PATH OF THE EXTERNAL MEDIUM

Having now defined the two aspects of detector perturbation (i.e., absolute perturbation and detectable perturbation) and contrasted the various contributing processes, it is clear that the important consideration in the assessment of spectrometer perturbation effects between experiment and calculation is the degree of detectable perturbation. Since this is dependent on the change of the ingoing neutron current over that entering the equivalent volume of unperturbed medium, it is evident that this change will, in turn, be dependent on the neutron scattering mean free path of the medium external to the detector. In particular, to ensure that the detectable perturbation is small relative to other uncertainties in a given measurement and associated calculation, the characteristic dimensions of the detector must be small

compared with the neutron scattering* mean free path in the external system. Notice that the absolute perturbation at the detector is dependent on the difference between the neutronic properties of the detector and the experimental system, whereas the detectable perturbation can be independent of these differences in neutronics properties provided the above condition is fulfilled.

In Fig. 1, for example, since the external medium is a vacuum, its scattering mean free path is infinitely large. It is, therefore, now possible to relax the constraint that detector 1 is 100% efficient, and still maintain the situation of no detectable perturbation since it is clearly impossible for neutrons scattered out of the detector to re-enter the sensitive volume and subsequently perturb the ingoing current. Due to scattering in the associated detector structure this situation is, of course, now contingent on the efficiency of detector 1 being determined from monoenergetic neutrons incident on the front face, and formally requires that the volume of detector 2 tends to zero so that back-scattered neutrons are eliminated.

In Fig. 2, deployment of a detector with characteristic dimensions small relative to the neutron mean free path in the scattering medium, minimizes those events analogous to neutron number 3, while neutrons number 1 and 2 do not contribute to the detectable perturbation, irrespective of the detector size (see above). Events such as neutron number 4 set a fundamental lower limit to the detectable perturbation since, if they cannot be allowed for in the detector response, they cause a detectable perturbation irrespective of the mean free path of the medium.

*"Scattering" here includes generalized secondary neutron production events (see Section 5 above).

This author has considered the detectable perturbation effects of a miniature (1.5 x 1.5 cm) NE 213 organic scintillation spectrometer employed in a lithium fluoride integral assembly for purposes of fusion reactor data assessment.[1,2] The neutron mean free path in this integral assembly was ~ 15 cm at 14 MeV reducing to only ~ 3 cm at 0.25 MeV and, as might be expected, the magnitude of the detectable perturbation in the measured neutron spectrum was a function of the neutron energy. Clearly, the requirement that the detectable perturbation be small in this experiment precluded the deployment of the more common larger ($\geq$ 5 x 5 cm) NE 213 spectrometers, especially at lower energies.

One last consideration here is the procedure one should adopt to predict the detectable perturbation of a prospective detector in a given experimental assembly. From the arguments above, it is evident that the difference in scalar fluxes from two formal transport calculations of the assembly, with and without the detector, does <u>not</u> provide the required result since this merely acknowledges the change in the system transport operator and, by Eq. (8), computes the absolute perturbation. In other words, this simply characterizes the perturbing effect of the detector on the neutron flux in the system and says nothing about the perturbing effect of the detector on its own measurements. Rather, from Eqs. (9) and (10), the expected difference between the perturbed experimental measurement and the ideal calculation (i.e., the expected detectable perturbation) follows from consideration of the change of the ingoing neutron current at the spatial coordinates of the detector surface with and without the presence of the detector. Due to the physical complexities of modeling a spectrometer in an experimental system, Eq. (9) will not usually be amenable to precise solution by either analytical analysis or

numerical finite difference techniques and recourse is necessary to Monte Carlo methods.[14] This would, however, require that conventional neutron Monte Carlo transport codes such as MORSE, TART, MCNP, etc., be modified from their conventional role of spectral flux determination to one of expressly scoring neutrons which cross the detector boundary two or more times in one history. Only in this way can the perturbation of the ingoing current and, therefore, the detectable perturbation, be determined.

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