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Performance analysis for neutronics benchmark experiments with partial adjoint contribution estimated by forward Monte Carlo calculation

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HIGHLIGHTS

- Performance estimation of nuclear-data benchmark was investigated.
- Point detector contribution played a benchmark role not only to the neutron producing the detector contribution but also equally to all the upstream transport neutrons.
- New functions were defined to give how well the contribution could be interpreted for benchmarking.
- Benchmark performance could be evaluated only by a forward Monte Carlo calculation.

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ABSTRACT

The author's group has been investigating how the performance estimation of nuclear-data benchmark using experiment and its analysis by Monte Carlo code should be carried out especially at 14 MeV. We have recently found that a detector contribution played a benchmark role not only to the neutron producing the detector contribution but also equally to all the upstream neutrons during the neutron history. This result would propose that the benchmark performance could be evaluated only by a forward Monte Carlo calculation.

In this study, we thus defined new functions to give how well the contribution could be utilized for benchmarking using the point detector, and described that it was deeply related to the newly introduced "partial adjoint contribution". By preparing these functions before benchmark experiments, one could know beforehand how well and for which nuclear data the experiment results could do benchmarking in forward Monte Carlo calculations.

1. Introduction

There are a lot of benchmark experiments carried out so far using massive samples and DT neutrons [1–5]. They are usually called "integral experiment" and have an important role of checking nuclear data for intermediate energies below 14 MeV as well as at 14 MeV especially for a fusion reactor. The author's group has thus been carrying out investigation of how well integral benchmark experiments with DT neutrons could play a benchmarking role for energies below 14 MeV [6–8].

From the results of the series study, especially for the benchmark experiments with DT neutrons, it was found that for gamma-ray spectrum measurements nuclear data at around 14 MeV were dominantly benchmarked. In return, for neutron spectrum measurements those below 14 MeV as well as at 14 MeV were found to be benchmarked fairly well, because neutrons could be rapidly moderated in sample materials. In conclusion, to make benchmark experiments more efficient, use of a spectrum shifter made of beryllium would be quite effective in order to make the incident neutron spectrum softer specifically for the gamma-ray spectrum measurements.

In case of carrying out the above benchmark analysis using experimental results with DT neutrons, it was thought to be reasonable and acceptable to set an energy boundary only at 10 MeV, meaning the number of the energy groups was just two, because the incident neutron is mono-energetic and so that it would be possible to think of neutron energy groups just as 14 MeV (source neutrons) and others (scattering neutrons). This means

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that discussion could be conducted using "neutron spectrum before last collision", which was defined as an energy spectrum of neutrons making neutrons or gamma-rays directly detected by a detector in the spectrum measurement. It was confirmed that this process of using two energy groups worked quite well for the benchmark performance analysis for the DT neutron incidence experiments. However, in a general case it seems to be clearly insufficient to employ only one energy boundary. Practically, a crucial problem would possibly exist as in the following. Now, if using finer energy bins for a general benchmark performance analysis, we can consider that there exist neutrons (A) making neutrons conveying contribution to a detector, and also there exist neutrons (B) making neutrons (A), and so on. The key point is that one has to think of not only neutrons (A) but also other neutrons created during a whole particle history starting from the source.

For this problem, we carried out a thought experiment to precisely examine which neutron (nuclear data for the energy) created during a transport history is benchmarked by the detector contribution [9]. The error sensitivity appearing between measurement and calculation was estimated and discussed by using a point detector normally used in Monte Carlo code calculations and assuming a small cross section perturbation. The error sensitivity in the benchmark analysis means which neutron's contribution causes discrepancy between experiment and calculation. From the result, the error sensitivity was found to be "equally" due not only to contribution directly conveyed to the detector, but also due to indirect contribution of neutron (A) making the neutron conveying the contribution to the detector, contribution of neutron (B) making neutron (A) and so on. From this concept, it would be expected to become possible to know from a forward Monte Carlo calculation carried out prior to a benchmark experiment, how well and which neutron (nuclear data for the energy) could be benchmarked in the benchmark experiment.

As well known, this kind of analysis would be realized in principle, if the adjoint function would be evaluated. At present, however, it is still difficult to estimate it especially in Monte Carlo calculations.

In the present study, based on the results of the thought experiment above, we discuss what kind of physical quantities derived from the forward Monte Carlo calculation should be taken into consideration to evaluate the benchmark performance especially from the standpoint of nuclear data. In the following chapters, we define "benchmark performance function", which shows how efficiently a value in each energy bin in the measured neutron spectrum could contribute to benchmarking of the nuclear data. And in addition, "benchmark performance density function" is defined, which shows how well and to which neutron (which energy of the neutron) the value could contribute to benchmarking. Then it will be shown that the function can be made up by simply summing up newly defined "partial adjoint contribution" constituting of the "adjoint portion" previously defined for the forward Monte Carlo calculation by Murata et al. [10].

2. Contribution to benchmarking by detector contribution

As described in Section 1, the error sensitivity in the benchmark analysis is "equally" due to every contribution directly and indirectly conveyed to the detector by ancient neutrons. Now we think of the benchmarking role concretely. In this case, it is necessary to see the detector contribution from a little different standpoint. Practically, now we want to see the "nuclear reaction", not the "contribution" made by the nuclear reaction, because we want to check the "nuclear reaction cross section". For this purpose, we focus not on "contribution" but on "neutron" inducing a nuclear reaction and making a contribution. Finally, we thus express a conclusion in Section 1 in other words, that is, detector contribution can play a benchmarking role not only for a neutron (A) "creating" (not conveying) contribution to the detector, a neutron (B) making (A), and so on, finally up to the source neutron.

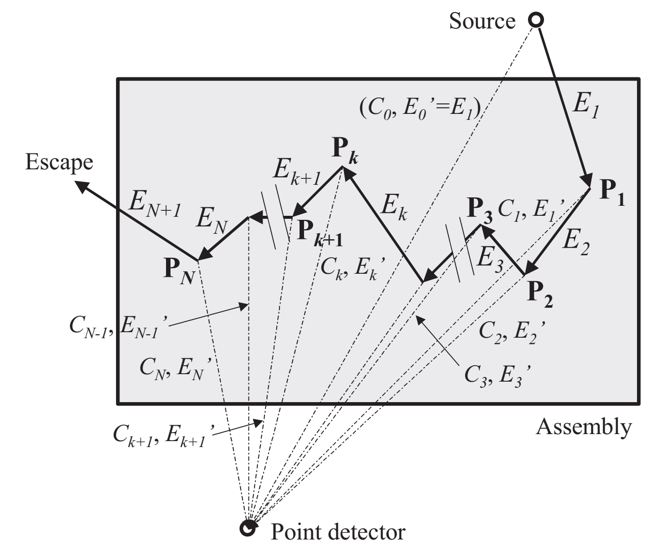

Fig. 1. Transport history of a particle and contribution made with a point detector. In this example, only scattering is assumed to occur N times at points P_i (i=1,2,. . .,N). In reality neutron multiplication reaction may take place. In that case, the particle transport will be split into two or more particle histories. Each contribution will be similarly added to its every ancient neutron till the source neutron, as described in the text.

Speaking more concretely, now assuming that a 14 MeV neutron starts from the source, and the behavior is calculated with a Monte Carlo code. We use here a point detector, because it is normally used for benchmark analyses of integral experiments like a leakage spectrum measurement. With the point detector very effective and efficient discussion would be possible, because each scattering point has detector contribution. It is known that it is difficult to use the point detector correctly. However, it would substantially enhance the statistics of the calculation. Now, we think of a neutron transport history as shown in Fig. 1. The source neutron has several scatterings in the assembly. As well known, using the point detector, the detector contribution, C_i, at scattering point P_i for a certain history is given by the following equation.

$$C_i = W_i \frac{p(\mu, E'_i)}{2\pi r^2} e^{-\int_0^r \Sigma(s,E'_i)\,ds}, \quad (1)$$

where W_i is the neutron weight, r is the distance from the current neutron position to the detector, and $p(\mu, E'_i) = 2\pi p(\mu, \varphi, E'_i)$ is the probability density function of a pseudo-neutron scattered toward the detector. Normally, no φ dependence can be assumed. μ is the angle between the neutron's flying direction and the vector from the current neutron position to the detector. E'_i is the energy of neutron conveying the contribution. $\Sigma(s, E'_i)$ is the macroscopic cross section of material at s, and s is the line from the current neutron position to the detector.

To simplify the discussion, we pick up the final contribution given to the detector, C_N. This contribution has its energy information, E'_i. This is created by a neutron having energy of E_N, as in Fig. 1, and forms a part of the measured spectrum. Clearly it can benchmark the cross section of the nuclear reaction induced by the neutron of energy, E'_i. However, in addition to that, according to Ref. [9], not only for it, but also for neutrons of E_{N-1}, E_{N-2}, and so on, and even for the source neutron of E_1, the contribution can benchmark. Surprisingly their benchmarking effectiveness was found to be the same as shown in Section 1.