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Reproducibility of (n,γ) gamma ray spectrum in Pb under different ENDF/B releases

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ABSTRACT

Radiative capture reactions are of interest in shielding design and other fundamental research. In this study the reproducibility of (n,γ) reactions in Pb when cross-section data from different ENDF/B releases are used in the Monte-Carlo code, MCNP, was investigated. Pb was selected for this study because it is widely used in shielding applications where capture reactions are likely to occur. Four different neutron spectra were declared as source in the MCNP model which consisted of a simple spherical geometry. The gamma ray spectra due to the capture reactions were recorded at 10 cm from the center of the sphere. The results reveal that the gamma ray spectrum produced by ENDF/B-V is in reasonable agreement with that produced when ENDF/B-VI.6 is used. However the spectrum produced by ENDF/B-VII does not reveal any primary gamma rays in the higher energy region ($E > 3$ MeV). It is further observed that the intensities of the capture gamma rays produced when various releases are used differ by a some margin showing that the results are not reproducible. The generated spectra also vary with the spectrum of the source neutrons. The discrepancies observed among various ENDF/B releases could raise concerns to end users and need to be addressed properly during benchmarking calculations before the next release. The evaluation from ENDF to ACE format that is supplied with MCNP should also be examined because errors might have arisen during the evaluation.

1. Introduction

Radiative capture reactions are very crucial in nuclear applications and fundamental research [1]. These reactions have been observed in many nuclides and are more dominant near the thermal neutron energy range. When a thermal neutron is absorbed by a target nuclide, an excited compound nucleus is formed. This nuclide decays to a lower energy state by emitting γ-rays. Subsequent decays leave the compound nucleus in its ground state.

The γ-ray transitions from resonance states are called primary γ rays, and the total radiation width of a resonance is the summation of partial widths to all final states [2]. In the field of nuclear application, radiative capture reactions can be used for elemental analysis through neutron activation analysis [3] or in shielding design especially where thermal neutrons are present. In both applications it is always necessary to understand the above processes and the characteristics of radiative capture gamma rays emitted. In shielding analysis the primary gamma rays are very important not only because of their contributions to the shielded dose, but also their heating effect that could lead to shield degradation [4]. Lead is one of the materials used in various shielding applications either as pure metal or in composite form [5–8]. Reliable information on the radiative capture reactions involving its isotopes (Pb) is necessary to avoid large uncertainties during shielding design. Recent shielding material characterization using ENDF/B-VII data and MCNP code revealed weaknesses in the radiative capture spectrum produced in Pb and W when irradiated by neutrons with a wide energy range [9]. Some obvious primary gamma rays attributed to the transition from the neutron separation energy to the ground state of some isotopes of Pb and W [1,10–12] were conspicuously absent from simulated spectrum. For example the 7.3 MeV that would be expected from the ^{207}Pb(n,γ)^{208}Pb reaction was not observed in the Pb spectrum. The energetic primary gamma rays associated with ^{183}W(n,γ)^{184}W and ^{182}W(n,γ)^{183}W were also absent in the tungsten spectrum. Since MCNP software that is commonly used for shielding design utilizes ENDF/B cross-section data [13], the deficiencies observed in our previous study are a source of concern to radiation protection experts because safety could be compromised through underestimation of the shielded dose. Furthermore, since the evaluated cross-section data that is used in Monte Carlo codes is partly from experimental data [14], the

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deficiencies in Monte Carlo calculations could raise questions on the accuracy of the original experimental data or the Monte Carlo Method. Nuclear data evaluators are always conscious of uncertainties in the original data and always try to make proper adjustments during benchmarking [13,15–17]. Any subsequent weaknesses which might have been overlooked during benchmarking need to be addressed as soon as they are noticed in order to maintain the integrity of the evaluated database. The main aim of this study was to investigate the reproducibility of the radiative capture gamma ray spectrum generated in Lead when different versions of the ENDF/B cross-section data are used in MCNP and outline the effects of any discrepancies on the end use application.

2. Methodology

The MCNP model was a 30 cm lead sphere similar to that of our previous study [9]. The neutron source was at the center of the sphere and four different neutron source spectra were used. Firstly the calculation was done with a fast neutron spectrum (0.1–1 MeV) declared in the source card. The calculation was repeated with an intermediate neutron spectrum (0.01–0.1 MeV), a slow neutron spectrum (0.001–0.01 MeV) and a Maxwell spectrum. The simulation was done on a neutron photon mode and F2 tally card was used to record the photon spectrum at the 10 cm radial surface (Fig. 1). Three different ENDF/B cross-section data namely ENDF/B-V, ENDF/B-VI.6 and ENDF/B-VII were used separately in the calculations. The Pb compositions were identical in each simulation but specified differently according to the adopted ENDF/B library. ENDF/B-V contains natural lead [18], while the simulation with other ENDF/B libraries assumed lead isotopes according to their natural abundances.

3. Results and discussion

The gamma ray spectrum produced when fast neutrons interact with Pb nuclei is shown in Fig. 2. It can be observed that for energies lower than 3 MeV the gamma ray spectra are in agreement when either ENDF/B release is used. However above 3.0 MeV, prominent radiative capture gamma rays are only observed when ENDF/B-V is used while ENDF/B-VI and ENDF/B-VII do not reveal any photopeaks. It's important to note that most of the photopeaks observed are associated with thermal neutrons though the source spectrum consisted of fast neutrons. This phenomenon is not surprising because the fast neutrons could be moderated before the radiative capture reactions occured. The discrepancy can be attributed to the databases and not the Monte Carlo code. This discrepancy in the databases could have arisen during upgrading to higher databases. In fact, such discrepancy has also been reported for copper isotopes during benchmarking calculations [19]. The discrepancies could also arise from the preparation of ACE files used in MCNP.

Figs. 3–5 show the gamma ray spectra in lead when slow neutrons, intermediate neutrons and Maxwell spectrum are used as source in MCNP respectively. It can be observed that in the low energy region, the trend follows that of the fast neutron source. However for higher energy region of the spectra only ENDF/B-VII does not reveal evidence of capture reactions. It is surprising that when the spectrum of the source neutrons is changed, ENDF/B-VI.6 produces very intense gamma ray spectra in the high energy region. When intermediate and slow neutrons are used, some of the photopeaks produced with ENDF/B-VI.6 data are more intense than those produced by ENDF/B-V (Figs. 3 and 4). However when a Maxwell spectrum is adopted for the neutron source in MCNP, ENDF/B-V produces more intense photopeaks than ENDF/B-VI.6 (Fig. 5). It is also observed that the intensity of primary gamma rays produced when fast neutrons are used (Fig. 2) is much lower than that produced in subsequent simulations probably due to differences in the population of neutrons in the optimum energy range for (n,γ) reactions. Probably the fast neutrons were not moderated to the optimum energy range for (n,γ) reactions specified in ENDF/B-VI.6. This phenomena also reveals that the spectrum of the source neutrons influences the reactions.

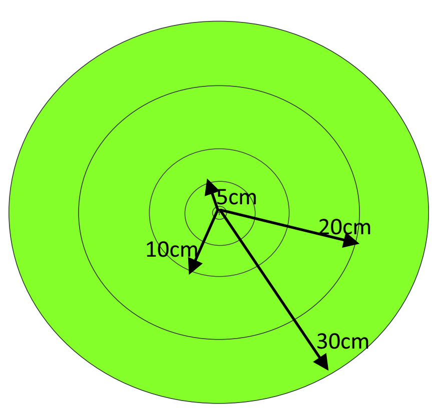

Fig. 1. The spherical model used in MCNP, the tally surface (10 cm radius) can be seen.

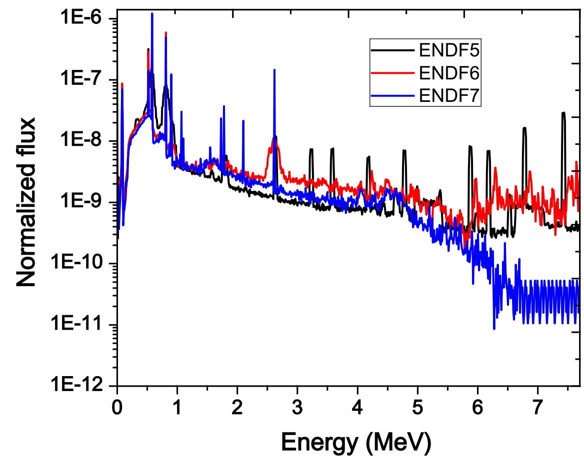

Fig. 2. Gamma ray spectrum in Pb when irradiated with fast neutrons.

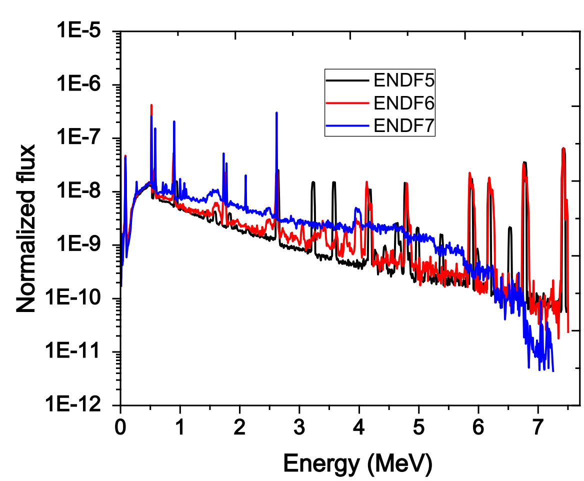

Fig. 3. Gamma ray spectrum in Pb when irradiated with intermediate neutrons.