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Indirect measurement of bremsstrahlung photons and photoneutrons cross sections of ^{204}Pb and Sb isotopes compared with TALYS simulations

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Abstract

A massive sliced Pb-target was irradiated by 20 MeV electrons and the bremsstrahlung photons produced plus the photoneutrons are applied to measure ^{204}Pb(γ, n) and ^{204}Pb(n, n') reactions cross section. The radioactivity induced inside the Pb-target slices was measured using γ-spectrometry. Incidentally, the ^{121}Sb(γ, n) and (n, γ) besides the ^{123}Sb(γ, n) nuclear reactions were also measured, since Sb is added in lead alloys to increase their rigidity. A detailed geometry of the Pb-target has been simulated using the GEANT4 code and the initial photons and neutrons fluence at the entrance of the Pb-target was calculated. The average cross sections of photonuclear reactions on ^{204}Pb and Sb isotopes as well neutrons inelastic reaction on ^{204}Pb and capture on ^{121}Sb were determined. Theoretical cross sections using the TALYS code have been simulated for all isotopes. An agreement between the experimental and simulated results appears while useful conclusions are presented regarding the nuclear parameters used in the simulations after comparison to experimental data.

Keywords: Photonuclear reaction; Neutron capture and inelastic reactions; TALYS; Activation detectors

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1. Introduction

Lead material is frequently involved in nuclear engineering experiments acting as fast neutron source. Intense neutron flux can be produced through spallation reactions on a solid target giving effectiveness on Accelerator Driven Systems [1–3]. Optimization of the efficiency on neutron reaction is achieved by maximizing each of the factors affecting the specific neutron reaction rate $R_{n\text{-react}} = \int \varphi(E).\sigma(E)dE$. Lead target is a good candidate in order to provide intense neutron flux [$\varphi(E)$], especially for neutrons with energy <1 MeV. Slow and intermediate neutrons in lead have higher cross sections for elastic scattering (>5 b) than absorption (<5 b). In particular, neutrons with energy <1 keV have also a nearly energy-independent elastic scattering cross section (∼11 b), generating small average lethargy $\xi \approx 0.01$. As a result, they have very high transparency through lead matter because only elastic scattering reactions occurred, due to small amount of neutrons absorbed (∼0.1 b) by lead nuclei [4]. Another fast neutron source can be based on an electron accelerator driven system, which acts as e–n converter because the bremsstrahlung photons produced by the interaction of high-energy electrons with lead, can induce further photonuclear reactions such as (γ, xn) and (γ, f) emitting fast neutrons [5–8]. Fast neutrons produced reach the intermediate energy range, after moderation by (n, xn) and (n, n') reactions, and then enter in the slow energy range by small iso-lethargic steps.

Lead cross sections data are important since they are involved in both experiments and simulations studies. A large number of publications concerning various types of nuclear reactions occurring in lead as well as its isotopes ^{204}Pb and $^{206-208}$Pb have been performed. The experimental results have supported nuclear data libraries [9] with data that occasionally are limited especially near the reaction threshold, like in the case of ^{204}Pb(n, n') reaction [10–12]. Besides, no data are available for photons induced reactions in ^{204}Pb. Lead alloys used to construct massive Pb-targets contain a certain amount % wt. of antimony to increase their rigidity (hard-lead), in addition to a few ‰ wt. of tin, iron and copper, zinc, silver or arsenic. As a result, the nuclear reactions of Sb, Sn and As isotopes can also be measured, which are essential concerning Sb isotopes since limited data (only two data-sets) are available in the literature and in disagreement between them [9]. Therefore, the data obtained after irradiation of a massive Pb-target by 20 MeV electrons was applied regarding to measure the photo-neutrons and bremsstrahlung photons cross sections of ^{204}Pb and Sb isotopes nuclear reactions.

In the present work, the radioactivity induced inside the lead target was measured using a γ-spectrometry system regarding to study the ^{204}Pb(γ, n) ^{203}Pb and ^{204}Pb(n, n') ^{204m}Pb reactions. Besides, the ^{121}Sb(γ, n) ^{120}Sb and ^{121}Sb(n, γ) ^{122}Sb as well as ^{123}Sb(γ, n) ^{122}Sb nuclear reactions were also studied. A detailed geometry of the Pb-target has been simulated using the GEANT4 code that transports effectively electrons, gamma and neutrons through matter. The initial photon and neutron fluences simulated at the entrance of the target due to the 20 MeV electron beam was applied to estimations of the average cross sections of photonuclear as well as neutron capture and inelastic reactions on ^{204}Pb and Sb isotopes. Moreover, theoretical cross sections on the basis of the Hauser–Feshbach statistical model using the TALYS code have been performed for all the reactions studied. Useful conclusions are presented regarding the nuclear parameters used in the simulations after comparison to experimental data.

2. Experimental

The target set-up consists of twenty (20) cylindrical lead disks 8 cm in diameter and 1 cm in length (Fig. 1a). The lead target disks-sections have mass ranges 559 to 569 g. The set-up was