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Excitation functions and cross section ratios for the formation of the isomeric pairs $^{102m,g;101m,g;99m,g}$Rh in the ^{nat}Pd(p,2pxn) reactions

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ABSTRACT

Excitation functions of the ^{nat}Pd(p,2pxn)$^{102m,g;101m,g;99m,g}$Rh reactions and the cross section ratios for the isomeric pairs ^{102m,g}Rh, ^{101m,g}Rh and ^{99m,g}Rh have been measured up to 42.61 MeV. The experiments were carried out using a stacked-foil activation technique. The proton beam intensity was determined based on the ^{nat}Cu(p,xn)^{62}Zn and ^{nat}Cu(p,xn)^{65}Zn monitoring reactions. The activities of the irradiated palladium and cooper monitor foils were measured using a HPGe γ-ray detector. The present experimental cross sections are compared with reference data and with the theoretical predictions from TENDL-2015 libraries. The cross sections for the nuclear reactions ^{nat}Pd(p,2pxn)^{102m,g}Rh were measured in the energy range of 20–40 MeV and the cross section ratios for all three isomeric pairs ^{102m,g}Rh, ^{101m,g}Rh and ^{99m,g}Rh produced in the ^{nat}Pd(p,2pxn) reactions are the first measurements.

1. Introduction

The charged particle-induced reaction cross sections of various elements are recognized as the most important parameter to study the structure of nuclei and to understand the nuclear reaction mechanism. They also strongly support in the production of medical radioisotopes, the calculation of the optimal parameters, and the measurement of the elemental impurities by using the activation analysis method [1–7]. However, in order to meet these requirements, it is necessary to have a rich database of experimental cross sections with the possible highest accuracy. Over the years, the efforts were made in the measurements of various nuclear data with different types of incoming projectiles, especially with protons.

In this work we have chosen the ^{nat}Pd(p,2pxn)$^{102m,g;101m,g;99m,g}$Rh nuclear reactions induced by protons with energies up to 42.61 MeV for the studies. It is interesting that these three nuclear reaction products exist in two states so-called the metastable (isomeric) state and the unstable ground state. The cross section ratios for the formation of these nuclear isomers might serve in the investigation of the mechanism of nuclear reactions. So far, in literature we have found only few experimental research works related to the nuclear reactions occurred in natural palladium [1,8–11]. These works were mainly focused on the measurements of the cross sections for the production of the following radionuclides: ^{110m}Ag, ^{106m}Ag, ^{105m,g}Ag, ^{104m,g}Ag, ^{103g}Ag, ^{100}Pd, ^{101}Pd, ^{105}Rh, ^{102m,g}Rh, ^{101m,g}Rh, ^{100g}Rh, ^{99m,g}Rh, ^{103}Ru, ^{97}Ru [1], ^{104m,g}Ag, ^{103}Ag [8], ^{105m,g}Ag, ^{106m}Ag, ^{110m}Ag, ^{100}Pd, ^{101m}Rh, ^{97}Ru [9] and ^{105}Ag [10,11]. Obviously, the experimental database for the proton induced reactions on palladium are still scanty, especially the cross sections for the production of the ^{nat}Pd(p,2pxn)^{102m,g}Rh, ^{nat}Pd(p,2pxn)^{101m,g}Rh and ^{nat}Pd(p,2pxn)^{99m,g}Rh reactions. The reasons for this are not obvious, but possibly may be due to the half-lives of some isotopes such as ^{101g}Rh ($T_{1/2}$ = 3.3 year) and ^{102m}Rh ($T_{1/2}$ = 3.742 year) are very long, and their activity measurements are very time consuming.

Among the investigated radionuclides, the ^{101m}Rh and ^{101g}Rh are considered as potential isotopes for medical applications [12,13]. It is believed that the obtained experimental nuclear cross sections can help to examine the probabilities for the production of the above mentioned rhodium isotopes, which are mostly missed in the earlier work [8–11]. In addition, from the measured cross sections we can also determine the cross section ratios for the isomeric pairs ^{102m,g}Rh, ^{101m,g}Rh and ^{99m,g}Rh. The present cross section ratios for the ^{102m,g}Rh, ^{101m,g}Rh and ^{99m,g}Rh isomeric pairs produced in the ^{nat}Pd(p,2pxn) reactions are the

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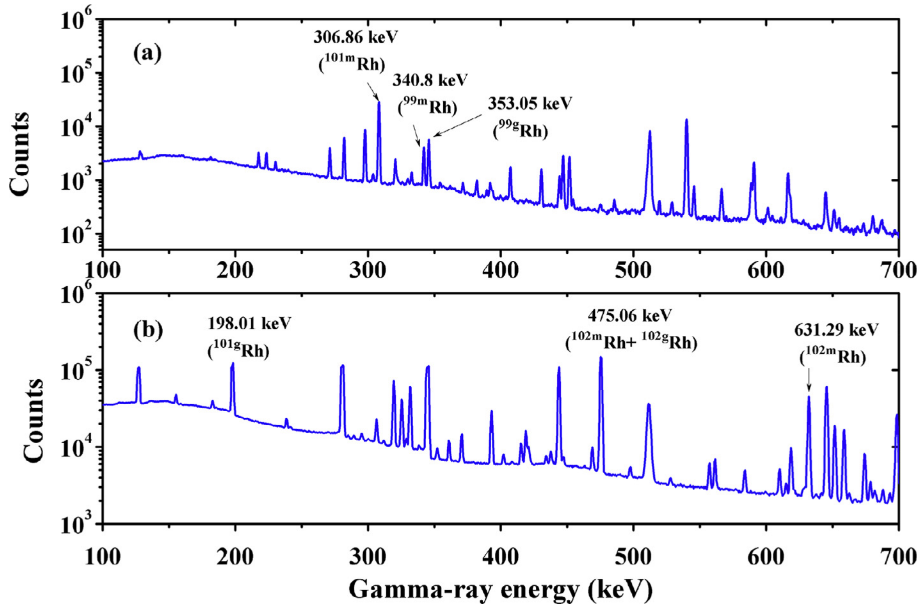

Fig. 1. Part of γ-ray spectrum from the ^{nat}Pd foil irradiated by 42.61 MeV proton beam: (a) t_i = 1h, t_w = 20 h and t_m = 30 min and (b) t_i = 1h, t_w = 260 d, and t_m = 4 d.

first measurements.

In this work, the experiment was carried out by using the stacked-foil activation and off-line γ-ray spectrometric technique. In fact, the measured γ-ray spectra composed a large number of γ-rays originated from different reaction products, causing difficulties in quantitative spectral analysis. Thus, in order to obtain accurate experimental results the efforts were made in choosing suitable experimental conditions and performing the necessary corrections for the γ-ray interference and counting losses.

Finally, the excitation functions of the $^{nat}Pd(p,2pxn)^{102m,g;101m,g;99m,g}Rh$ reactions are compared with the corresponding reference data and with the theoretical predictions from the TENDL-2015 data library [14]. In addition, the present cross section ratios of the isomeric pairs $^{102m,g;101m,g;99m,g}Rh$ are also compared with the corresponding data of the photonuclear reactions $^{nat}Pd(\gamma,pxn)^{102m,g;101m,g;99m,g}Rh$ [15]. The comparison of these two sets of cross section or yield ratios of the $^{102m,g}Rh$, $^{101m,g}Rh$ and $^{99m,g}Rh$ isomeric pairs produced through different reactions: $^{nat}Pd(p,2pxn)$ and $^{nat}Pd(\gamma,pxn)$ can provide useful information about the reaction channel effect.

2. Experimental details

The stacked-foil irradiation technique in combination with off-line γ-ray spectrometry was employed in this study. For the purpose of the irradiation, the natural palladium foils (Alfa Aesar, purity > 99.99%, thickness 100 μm) were stacked with copper monitors (Alfa Aesar, purity 99.9999%, thickness 55 μm) and some other metallic foils served as energy degraders. The stacked-foils with the same size of 10 mm × 10 mm covered by an aluminum foil of 200-μm thickness were irradiated by a proton beam with energy of 45 MeV at the Korea Institute of Radiological and Medical Science (KIRAMS), Korea [6,8]. The irradiation was performed for one hour with the proton beam intensity of 100 nA.

After irradiation, the γ-ray spectra of the palladium and copper foils were measured to identify the reaction products and determine their activities. The measurements were carried out by using a well calibrated γ-spectroscopy system. It consists of a coaxial high purity germanium (HPGe) detector (ORTEC- GEM- 20180-p) coupled to a PC-based multichannel analyzer. The energy resolution and relative efficiency of the detector at the 1332.5-keV γ-ray of ^{60}Co are 1.8 keV and 20% relative to a 3″ × 3″ NaI(Tl) detector, respectively. The detector efficiencies as a function of both the photon energy and the sample-detector distance were measured by using the standard γ-ray sources ^{152}Eu, ^{60}Co, ^{137}Cs and ^{133}Ba. The nuclear decay data of these γ-sources are taken from Ref. [16].

The first measurement of the irradiated foils was started about 8 h after the end of the irradiation. The long waiting time was needed in order to reduce the Compton background. Due to the half-lives of the radioisotopes of interest from both the palladium and copper are rather long, varied from some hours to several years, therefore in order to follow their decay and identify the possible interferences, more γ-ray spectra must be taken at different waiting times. For each measurement, the accurate sample-detector geometry was taken into account by using a well designed sample holder. In addition, the attention was also made to reduce the dead-time and the coincidence summing effect. For these purposes, the sample was positioned at a distance of 10 or 15 cm from the surface of the detector. The time duration for each measurement was considered based on the accumulated counts of the γ-ray peaks of interest. Due to the half-lives of the radio-nuclides of interest produced from the $^{nat}Pd(p,2pxn)$ reactions such as ^{102m}Rh ($T_{1/2}$ = 3.742 year), ^{102g}Rh ($T_{1/2}$ = 207.3 day) and ^{101g}Rh ($T_{1/2}$ = 3.3 year) are relatively long, the measurements were performed over a long time. The last γ-ray spectrum was taken about 300 days after the end of the irradiation. Typical γ-ray spectrum of the irradiated palladium foil is shown in Fig. 1. The nuclear spectroscopic data such as half-lives, γ-ray energies and intensities of the reaction products of interest [16] along with the probable contributing reactions from natural palladium and monitoring copper as well as threshold energies of nuclear reactions [17] are listed in Table 1.

3. Data analysis

In order to determine the excitation functions of the $^{nat}Pd(p,2pxn)^{102m,g;101m,g;99m,g}Rh$ reactions and cross section ratios of the $^{102m,g}Rh$, $^{101m,g}Rh$ and $^{99m,g}Rh$ isomeric pairs, we need to determine the energy and the intensity of the incident proton beam as well as the activity of each reaction product of interest.

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