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Measurements and assessment of $^{12}C(d,p\gamma)^{13}C$ reaction cross sections in the deuteron energy range 740–2000 keV for analytical applications

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ABSTRACT

The total cross sections of the $^{12}C(d,p\gamma_1)^{13}C$ (Eγ = 3089 keV), $^{12}C(d,p\gamma_2)^{13}C$ (Eγ = 3684 keV) and $^{12}C(d,p\gamma_3)^{13}C$ (Eγ = 3854 keV) reactions, as well as differential cross sections for (d,p_o), (d,p_1) reactions and (d,d_0) elastic scattering were determined in the 740–2000 keV deuteron energy range using a self-supporting natural carbon foil and detecting the gamma-rays and particles simultaneously. In order to test the validity of the measured gamma-ray producing cross sections, benchmark experiments were performed using kapton foils with two different thicknesses. Both the obtained gamma- and particle production cross section results were compared with data existing in literature, and in the case of (d,p_o) the experimental differential cross section data were compared also with the theoretical evaluated values.

1. Introduction

Particle Induced Gamma-ray Emission (PIGE) spectroscopy is an excellent tool to measure the concentration of light elements such as carbon. The $^{12}C(d,p\gamma)^{13}C$ nuclear reaction has already been applied in materials science for the determination of carbon in steels [1] and to characterize high purity, high performance thin films produced by metal–organic chemical vapour deposition (MOCVD) technique. Regarding the characterization of thin films, the advantage of the PIGE method is its sensitivity; it is capable to detect rather low carbon concentrations and C/O ratios in the presence of different kind of substrates [2,3].

Gamma-ray production yields in deuteron induced nuclear reactions (d-PIGE) for thick targets were published in [4] for several deuteron energies; however, for precise quantitative analysis, the cross section of the reaction as a function of deuteron energy is needed. To our best knowledge, the following cross section measurements exist in literature: Tryti et al. [5,6] studied primarily the behavior of this reaction in terms of nuclear physics, while the aim of the later measurements [7,8] was the application of the resulted cross sections for elemental analysis (archaeometry and geology, respectively). The comparison of the published cross sections revealed rather large discrepancies.

The aim of this work is to determine reliable cross section data for the $^{12}C(d,p\gamma)^{13}C$ nuclear reaction by carrying out the measurement of gamma-ray producing cross sections with the detection of gamma- and particle yields simultaneously. In this paper we report on the measurements of the total $^{12}C(d,p\gamma_1)^{13}C$ (Eγ = 3089 keV), $^{12}C(d,p\gamma_2)^{13}C$ (Eγ = 3684 keV) and $^{12}C(d,p\gamma_3)^{13}C$ (Eγ = 3854 keV) reaction cross sections, as well as differential cross sections for (d,p_o), (d,p_1) reactions and (d,d_0) elastic scattering, respectively. In order to test the measured cross sections in relation to the thick target yields, benchmark experiments were performed. Both the obtained gamma-ray and particle production cross section results were compared with data existing in literature, and in the case of (d,p_o) it was a possibility to compare the experimental differential cross section data with the theoretical evaluated values published by Abriola et al. [9] recently.

The present work is part of a Coordinated Research Project organized by IAEA [10,11] and the experimental results will be incorporated into IBANDL (Ion Beam Analysis Nuclear Data Library, www-nds.iaea.org/ibandl/).

2. Experimental

The measurements were carried out at the 5 MV Van de Graaff accelerator of Atomki. The energy calibration of the accelerator for protons was performed with the 992 keV resonance of the $^{27}Al(p,\gamma)^{28}Si$ reaction. Besides the calibration with protons, the 1449 ± 1.5 keV resonance [12] of the $^{12}C(d,p\gamma)^{13}C$ reaction was also used to check the energy calibration.

The experimental set-up consisted of a target chamber with a long Faraday cup, a coaxial type HPGe detector of 170 cm^3 volume

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positioned at an angle of 55° relative to the beam direction at a distance of 9.5 cm from the target, and an ion implanted Si detector with 500 μm active depth and 13 keV energy resolution was placed at an angle of 135° relative to the beam direction at a distance of 4.15 cm from the target. A copper collimator with a hole diameter of 3 mm was used in front of the Si detector. The determination of the solid angle of the Si detector was done with a Th(B + C) radioactive source with a well known activity. The solid angle was found to be 4.11 ± 0.10 msr. The detailed description of the experimental set up including the absolute efficiency determination of the HPGe gamma detector is presented elsewhere [13].

The target was a self-supporting natural carbon foil (thickness: 1.9×10^{18} atom/cm^2) with an evaporated palladium layer on its back surface (thickness: 2.7×10^{17} atom/cm^2). The number of target nuclides was determined with α-RBS technique directly before and after the cross section measurements and under the same experimental conditions using the SIMNRA program [14]. The applied α-energy was 1.5 MeV. At this incident energy the backscattering of alpha particles can be considered as pure Rutherford on both C and Pd [15]. In order to check the stability of the target, and also the possible build-up of carbon on its surface, the thin target gamma-ray and proton yields were re-measured in several energy points directly after finishing the actual yield measurements. Comparing the α-RBS thickness data that was obtained before and after the yield measurements, and also on the basis of the gamma-ray and proton yield re-measurements, we can conclude that the damage of the target and the carbon build-up on its surface were below 5%, so within the uncertainties; in addition, the overall sum of these deviations was close to zero. Figs. 1 and 2 show the gamma-ray and particle spectra of the target measured simultaneously at 2.0 MeV deuteron energy. The interaction of the beam with the carbon contaminants of the experimental set-up has to be taken into consideration because it also gives a contribution to the measured gamma-ray yields thus decreases the accuracy of the calculated cross sections. Our test measurements carried out with an empty target holder at different gamma energies showed that this contribution is (3 ± 1)%, thus we corrected our final results with this value.

Gamma-ray yields for the 3089, 3684 and 3854 keV gamma-lines of the $^{12}C(d,p\gamma)^{13}C$ reaction and $^{12}C(d,p_0)^{13}C$, $^{12}C(d,p_1)^{13}C$, $^{nat}C(d,d_0)^{nat}C$ reaction particle yields were measured. The measurements were performed starting from 2000 keV deuteron energy and descending to 740 keV with 2–20 keV steps depending on the structure of the excitation function, and was repeated at certain deuteron energies several times. Typical beam current and collected charge were 25 nA and 7 μC, respectively. The simultaneous collection of gamma-ray and particle spectra as it was proposed in reference [11] has the advantage of the independent

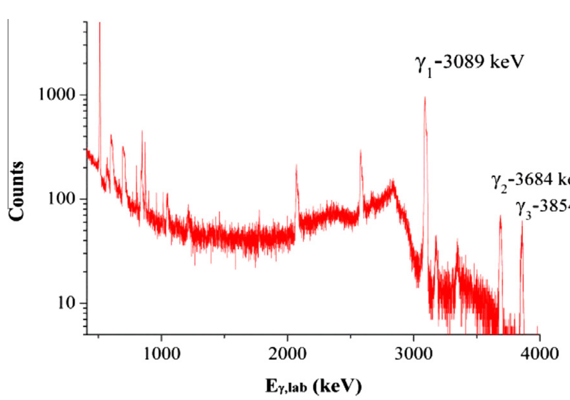

Fig. 1. Gamma-ray spectra of the C-Pd target at 2.0 MeV deuteron energy.

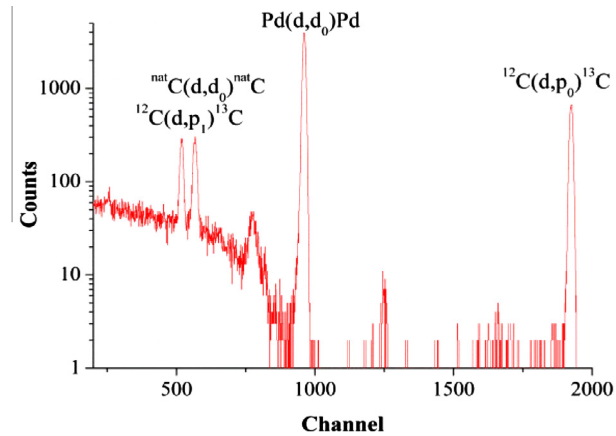

Fig. 2. Particle spectra of the C-Pd target at 2.0 MeV deuteron energy. (The low energy background is due to the scattering from the wall of the chamber, the peak at channel no. 750 is regarded as electronic noise.)

determination of the beam charge with the RBS monitoring of the Pd layer, which helps to avoid systematic and stochastic uncertainties of charge integration.

3. Cross section calculations and discussion of the results

3.1. Gamma-ray production cross sections

The total gamma-ray production cross section was determined according to the following equation:

$$\sigma_\gamma(E_0,\theta) = \frac{Y_\gamma(E_0,\theta)}{N_p N_t - C^{\varepsilon_{abs}}(E_\gamma)} \quad (1)$$

where $Y_\gamma(E_0, \theta)$ is the measured γ-ray yield (i.e. the net area of the γ-ray peak) at deuteron energy E_0 and γ-ray detection angle θ, N_p is the number of incident projectiles, $N_{t\text{-}c}$ is the number of carbon nuclei per square centimeter and $\varepsilon_{abs}(E_\gamma)$ is the absolute detection efficiency of the HPGe detector at the corresponding gamma-ray energy [10]. This formula is valid only if the cross section is varying only little within the target thickness, which requirement is satisfied approximately for the entire energy range except at resonant energies. Therefore, the calculated and presented gamma-ray production cross section values are considered as averaged ones for the finite thickness target.

To avoid the errors stemming from the direct measurement of incident charge, we calculated the number of incident projectiles N_p from the following equation:

$$N_p = \frac{Y_S(E_0,\beta)}{\frac{d\sigma_{Ruth}(E_0,\beta)}{d\Omega} * \Omega\varepsilon N_{t\text{-}Pd}} \quad (2)$$

where $Y_S(E_0, \beta)$ is the measured scattered particle yield for the palladium layer on the target (i.e. the net area of the scattered projectile peak) measured at deuteron energy E_0 and particle detection angle β, $d\sigma_{Ruth}(E_0, \beta)/d\Omega$ is the Rutherford cross section for palladium at deuteron energy E_0 and particle detection angle β and $N_{t\text{-}Pd}$ is the number of palladium nuclei per square centimeter [10].

With this method, we had to ascertain the target nuclide numbers with high precision for both components, and determine the parameters of the experimental system, the solid angle of the particle detector and the absolute efficiency of the HPGe detector. In the calculation of the elastic backscattering cross section for palladium, the changes in the energy of deuterons while moving through the carbon layer had to be taken into account, too.