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Differential cross sections measurement of ^{28}Si(p,p$^{/}\gamma$)^{28}Si and ^{29}Si(p,p$^{/}\gamma$)^{29}Si reactions for PIGE applications

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ABSTRACT

Differential cross sections for gamma-ray emission from the ^{28}Si(p,p$^{/}\gamma$)^{28}Si ($E_\gamma = 1779$ keV) and the ^{29}Si(p,p$^{/}\gamma$)^{29}Si ($E_\gamma = 1273$ keV) nuclear reactions were measured in the energy range of 2.0–3.2 MeV and 2.0–3.0 MeV, respectively. The thin Si targets were prepared by evaporating natural SiO onto self-supporting Ag films. The gamma-rays and backscattered protons were detected simultaneously. An HPGe detector placed at an angle of 90° with respect to beam direction was employed to collect gamma-rays while an ion implanted Si detector placed at a scattering angle of 165° was used to detect backscattered protons. The great advantage of this work is that differential cross sections were obtained with a procedure irrespective of absolute value of the collected beam charge.

1. Introduction

Particle induced gamma-ray emission (PIGE) with proton beam is a powerful analytical technique which measures prompt gamma-rays originated from nuclear reactions produced by proton beam bombarding the solid sample to determine the concentration of light elements such as Si. This technique is more applicable for light elements than heavy ones because of the Coulomb barrier effect at low energy particles. PIGE can be used as a complementary technique with particle induced X-ray emission (PIXE) for low-*Z* elements ($Z < 15$) since in PIXE measurements, contrary to PIGE, X-rays corresponding to these elements are strongly attenuated in the sample and also efficiency of detector for these low energy X-rays is small.

PIGE quantitative analysis of thick samples is usually performed by comparing the measured data with those of standard samples with similar composition [1]. If the composition of the sample considerably deviates from that of the standard one, serious errors may arise due to different stopping powers of protons in the matrices of the sample and standard. It is known that reliable values of the cross section data allow the application of PIGE technique for analysis of light elements regardless of the standard sample. This is performed by integrating nuclear reaction cross section along the depth of the sample employing suitable code [2–4].

According to best knowledge of authors, gamma-ray production cross-sections of the ^{29}Si(p,p$^{/}\gamma$)^{29}Si reaction have not yet been reported in the 2.0–3.0 MeV energy range and only few studies have been published for spectroscopic purposes in the literature [5–7]. For the ^{28}Si(p,p$^{/}\gamma$)^{28}Si reaction, the only published cross section data is the work of Boni et al. [8]. Their measurements were performed at proton energies of 3.0 to 3.8 MeV and at $\theta_{lab} = 90°$ using a target consisting of a 165 μg/cm^2 thin SiO$_2$ target evaporated on a Nuclepore filter. Moreover, thick target yields of the two reactions are reported both in suitable energy ranges for PIGE applications [9,10] and in some selected single points [11,12].

The purpose of the present research work is to provide reliable PIGE differential cross section data, for the ^{28}Si(p,p$^{/}\gamma$)^{28}Si ($E_\gamma = 1779$ keV) and ^{29}Si(p,p$^{/}\gamma$)^{29}Si ($E_\gamma = 1273$ keV) reactions in the laboratory energy range of 2.0–3.2 MeV and 2.0–3.0 MeV, respectively. This research work is a part of coordinated research project organized by IAEA [13].

2. Experimental procedure

The experimental work was carried out on the 45° right beamline of the 3 MV Van de Graaff electrostatic accelerator of Nuclear Science and Technology Research Institute (NSTRI) in Tehran. The measurements were performed in energy steps of 1–2 keV in resonance regions and variable energy steps of 10–40 keV in off-resonance regions.

Deflection of the proton beam by 45° passing through the 3 mm wide stabilizing slit of Van de Graff accelerator and the 3 mm wide fixed aperture placed 280 cm farther, ensures a beam dispersion of less than 1 keV at $E_p = 992$ keV. The field strength of the analyzing magnet was adjusted for each energy point and then measured by

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an NMR fluxmeter. The proton beam energy was calibrated using the 991.88 keV resonance of ^{27}Al(p,γ)^{28}Si reaction [14] and the 1880.44 keV threshold energy of ^{7}Li(p,n)^{7}Be reaction [15]. The targets used for these measurements were a 60 µm-thick Al foil and a LiF pellet, respectively. After calibration, uncertainty of the proton beam energy was found to be about 2 keV.

The proton beam was collimated using two fixed apertures 5 mm and 3 mm in diameter positioned at 250 cm and 87 cm from the target (center of the chamber), respectively. The beam spot size on the target was about 4 mm in diameter. The target was oriented inside the reaction chamber so that the incident beam direction makes an angle of 45° with normal to the target.

The reaction chamber which is recently designed and fabricated in our lab can be used for simultaneous measurements of PIGE, RBS and PIXE. It is made of an aluminum alloy with a lining of tin (Sn) to minimize the PIGE background radiation. Our experimental setup includes a coaxial type HPGe detector, a silicon detector, an isolated target holder and a Faraday cup electrically connected to the target to measure the incident beam current. During the measurements, vacuum pressure in the chamber was about 5×10^{-5} mbar. Fig. 1 shows a schematic diagram of the experimental setup. Gamma-rays were detected by a P-type HPGe coaxial detector with crystal size of 6.58 cm × 6.58 cm and an active volume of 213 cm^3 placed at right angle with respect to the beamline direction and at a distance of 51.9 mm from the target center. The nominal efficiency and resolution of the detector was 50% and 1.95 keV for 1.33 MeV, respectively.

The detector was protected by a 5 cm-thick cylindrical lead shield to reduce the gamma-ray background. Moreover, the inner wall of the lead shield was covered with a 3 mm-thick copper (Cu) lining to reduce the X-ray production from the lead. The detector employed for detection of scattered protons was an ion-implanted silicon detector with 25 mm^2 active area, 300 µm thickness and 13 keV energy resolution placed at an angle of 165° relative to incident beam direction. Based on the geometrical method, the solid angle of Si detector was calculated to be 0.75 ± 0.02 msr.

The two employed targets were prepared by evaporation of natural SiO onto thin Ag films using the technique described in Refs. [16,17]. RBS measurements with 2 MeV alpha beam were performed to determine the stoichiometry as well as the thickness of the target layers. By simulation of the RBS spectra with the SIMNRA code [18], composition of the SiO layer was obtained to be 45% natural Si and 55% O. Moreover, the thickness of SiO and Ag layers of the first target were found to be 25.6 ± 1.8 µg/cm^2 and 97.5 ± 3.6 µg/cm^2, respectively. The first target was used in the 2.0–3.0 MeV incident beam energy range, while the second one consisting of 53 ± 4 µg/cm^2 SiO evaporated onto 82.3 ± 3.0 µg/cm^2 Ag film was employed in the beam energy range of 3.0–3.2 MeV. Based on SRIM calculations [19], the proton beam energy loss in SiO layers were found to be 4.3–3.2 keV and 6.5–6.2 keV for the first and second targets, respectively. The incident beam currents were chosen within 100–600 nA depending on the beam energy to keep the counting rate of both detectors low enough, so that the pile up effects were negligible and required corrections for dead time of HPGe and particle detector were less than 10% and 1%, respectively. The accumulated beam charge was chosen to be between 5 and 400 μC at each energy point depending on the statistics. In this way, statistical errors in the off-resonance and resonance regions were obtained 5–10% and 1–3%, respectively.

To eliminate systematic and stochastic uncertainties related to the determination of the absolute values of the collected beam charge, we followed the procedure recommended by Abriola et al. [13] by employing a heavy element such as Ag, as part of the target, for normalization of the cross section against Rutherford backscattering from Ag.

3. Experimental results and discussion

The absolute differential cross section values $\left(\frac{d\sigma}{d\Omega}\right)_{\gamma,\mathrm{Si}}(E,\theta)$ at the energy E and at detection angle θ were determined from the following equation:

$$\left(\frac{d\sigma}{d\Omega}\right)_{\gamma,\mathrm{Si}}(E,\theta) = \frac{1}{4\pi}\frac{Y_{\gamma,\mathrm{Si}}(E)}{Y_{\mathrm{p,Ag}}(E^{/})}\cdot\left(\frac{d\sigma}{d\Omega}\right)_{R,\mathrm{Ag}}(E^{/},\beta)\cdot\frac{\Omega_{\mathrm{p}}\cdot\varepsilon_{\mathrm{p}}}{r\varepsilon_{\mathrm{abs}}(E_{\gamma})} \qquad (1)$$

where $Y_{\gamma,\mathrm{Si}}\,(E,\theta)$ is the gamma yield at the mean energy $E = E_0 - \frac{\Delta E_{\mathrm{SiO}}}{2}$ (E_0, ΔE_{SiO} are the incident proton energy and energy loss in SiO film, respectively) and at the detection angle θ; $\boldsymbol{\varepsilon}_{\mathrm{abs}}(E_{\gamma})$ is the absolute

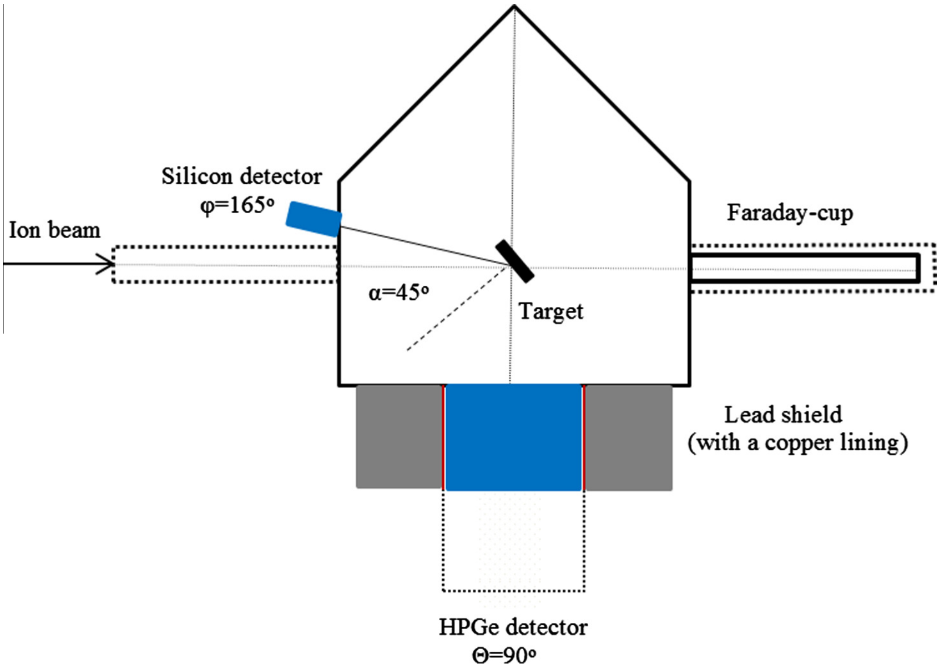

Fig. 1. Schematic diagram of the experimental setup for PIGE measurements (not to scale).