Proton inelastic scattering cross section measurements on ^{16}O and ^{28}Si

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Abstract. A $(p, p'\gamma)$ experiment was performed at the Tandem accelerator of IFIN-HH (Bucharest) with the purpose of measuring the proton inelastic cross-sections on ^{16}O and ^{28}Si. The goal was to investigate to which extent the neutron cross-sections on these nuclei can be inferred from those obtained with charged particles (i.e., protons). In doing so, we are trying to exploit the isospin symmetry by taking under consideration that the chosen targets are N = Z nuclei and, consequently, two mirror nuclei are formed in the (p, p') and (n, n') reactions. The experimental setup consisted of two HPGe detectors with 100% relative efficiency placed at 110° and 150° relative to the direction of the incident proton beam. The incident protons, which had energies ranging from 6 up to 17 MeV, were scattered on a thick quartz (SiO_2) target. A Faraday cup was used to integrate the beam current, thus allowing an absolute determination of the γ production cross sections. We will briefly describe the data analysis procedure, the experimental particularities and difficulties and some preliminary results of the γ production cross sections for the most intense transitions both in ^{16}O and ^{28}Si.

1. Introduction

The predominant contribution to nuclear reactor's non-local heating comes from the fission γ's and from the neutron's slowdown. In this context an investigation of the de-excitation of oxygen and silicon through γ emissions following neutron inelastic scattering will help for a better understanding of the γ sources inside nuclear reactors, information relevant for building the next generation (i.e., Gen. IV) of such facilities. Therefore, the very precise measurement of neutron inelastic cross sections on ^{16}O and ^{28}Si represents an important goal.

Oxygen is one of the most abundant elements on Earth. It can be found in water, air, organic matter and all oxides. ^{16}O is the most abundant oxygen isotope; it is also of particular interest for nuclear applications, being one of the six isotopes under focus by the CIELO collaboration [1] and, notably, it is on the High Priority Request List (HPRL) of NEA [2]. Gas-cooled fast reactors (GFRs) use helium in the cooling system and have silicon as a component of the fuel rods and of the reflector. This is why ^{28}Si is also on HPRL. For both these isotopes the requested uncertainty for the neutron inelastic cross section should be reduced from 14%–50% down to 3%–5% [2], which represents a very serious experimental challenge.

Neutron beams are harder to produce and much harder to control than the charged particle ones. Due to this fact, the scientific community proposed the idea of trying to infer neutron reaction cross sections from charged particle ones- the so-called surrogate reactions method [3]. Numerous attemps were made during the past decade (see [4–9]). In some cases the cross sections determined via the *surrogate ratio method* agree rather well with the cross sections determined through the direct measurement of the reaction of interest, the differences being of the order of 10% or smaller [10]. Therefore, is relevant to establish if and when the surrogate method is applicable. So far this technique was applied only in neutron fission and capture reactions. In this work we intend to investigate if a similar idea can be applied to other types of neutron reactions, particularly in the case of inelastic scattering.

The neutron inelastic scattering cross sections on ^{28}Si were already measured very precisely by our group using Geel Electron Linear Accelerator (GELINA) [11] and Gamma Array for Inelastic Neutron Scattering (GAINS) [12] setups of European Commission-Joint Research Center (EC-JRC) Geel, Belgium. The results have been published in Ref. [13].

We recently performed, also, a measurement of neutron inelastic scattering on ^{16}O using the same experimental facility. The data analysis is currently ongoing.

Reference [13] made a comparison between ^{28}Si$(n, n'\gamma)^{28}$Si and ^{25}Mg$(\alpha, n\gamma)^{28}$Si reactions. These

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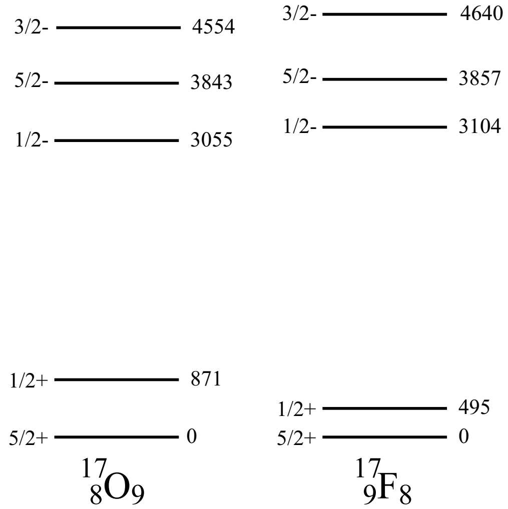

Figure 1. The partial level scheme of ^{17}O and ^{17}F. The high similarity between the two level schemes is mainly due to the isospin symmetry.

reactions proceed through the same compound nucleus (CN) and, therefore, in a naive interpretation of Bohr's hypothesis [14] the γ production cross sections could have similar shapes and/or absolute values.

In this paper we study the ^{16}O(p, $p'\gamma$)^{16}O reaction. The more general context of the present work is to investigate the next pair of nuclear reactions: ^{16}O(n, $n'\gamma$)^{16}O vs. ^{16}O(p, $p'\gamma$)^{16}O and similarly for ^{28}Si. During the reactions two mirror nuclei (i.e., ^{17}O and ^{17}F) are formed. In this case we chose as targets two N = Z nuclei because we try to exploit the isospin symmetry. This is the case considering that the isospin symmetry manifestation in the mentioned mirror nuclei generates very similar level schemes (see Fig. 1), for which the corresponding γ production cross sections could be comparable or at least proportional.

2. Experimental setup

The experiment was performed at the 9 MV Tandem facility of IFIN-HH, Bucharest [15,16]. A proton beam with energies ranging from 6 to 17 MeV, with 1 MeV steps, was scattered on a thick quartz (SiO_2) target. For each incident proton energy the data were accumulated for 2–3 hours while the detection system's dead time losses were kept at reasonable values (under 6%). The areal density of the target was 34.93 mg/cm^2 . A Faraday cup was placed after the target, as close as possible, in order to collect the protons that passed through it (see Fig. 2).

The detection system consisted of two HPGe detectors with 100% relative efficiencies (see Fig. 2). They were placed at 110° and 150° relative to the proton beam direction and at a distance of 15.45 cm and 18.25 cm, respectively. We used a TNT2 [17] digitizer with a sampling frequency of 100 MHz.

3. Experimental particularities and difficulties

During the experiment we encountered some specific difficulties. The first example of such difficulties is given by the fact that Doppler broadening was observed

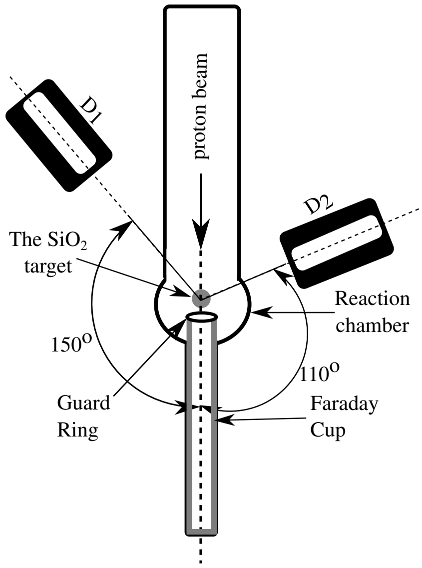

Figure 2. A schematic drawing of the experimental setup. It consisted of two detectors placed at 110° and 150° relative to the proton beam direction. A Faraday cup was placed at the back of the reaction chamber for collecting the protons.

for transitions corresponding to those levels which had lifetimes comparable to the time necessary for the emitting nucleus to be completely stopped inside the quartz target. The integration of these deformed γ peaks posed, in some cases, relevant difficulties.

Given the fact that the energies of the γ rays of interest are very high (for example the detected transition in ^{16}O has 6128 keV), we had to extrapolate the detectors efficiencies to these high γ energies. The extrapolation was done using MCNP6 simulations [18,19]. The experimental efficiency curve was obtained using a ^{152}Eu energy calibration source which had an activity of 266(6) kBq at the beginning of the experiment.

Considering that we used a thick target, the proton energy loss inside the target could not be neglected. In this context, for each incident proton energy value, we assumed that after entering the target the proton energy has a random variable behaviour. The associated distribution was considered to be the uniform probability distribution function and the mean energy and its uncertainty were calculated accordingly. These values were used in the plotting of Figs. 3 and 4.

Finally, during our experiment we registered reasonably high counting rates. The dead time correction procedure will be detailed in the next section.

4. Data analysis procedure

Using γ spectroscopy techniques we were able to extract proton inelastic scattering *absolute* γ production cross sections. From the data collected from the detectors and via our data analysis software we obtained the amplitude spectra for every incident proton energy. In these spectra the γ rays of interest from silicon and oxygen were identified and their corresponding peaks were integrated. The Faraday cup measured the proton beam intensity.

For calculating the differential cross section we used the next formula:

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi} \cdot \frac{N_\gamma \cdot A}{N_p \cdot \varepsilon_{det} \cdot \rho_x \cdot f}. \qquad (1)$$

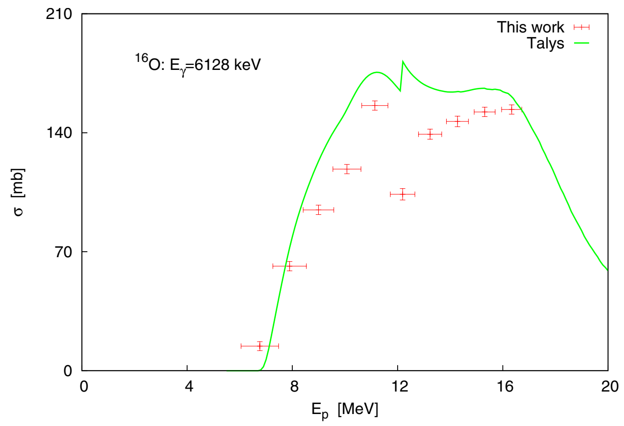

Figure 3. The γ production cross section for the E_γ = 6128.63 keV transition in ^{16}O. The experimental results are compared with theoretical calculations done with the Talys 1.8 code.

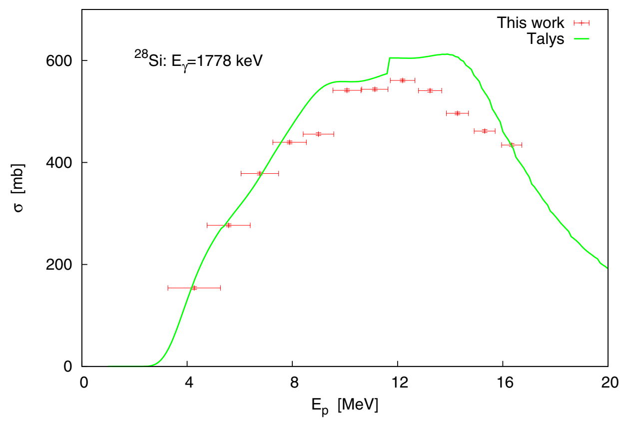

Figure 4. The γ production cross section for the first transition in ^{28}Si. The experimental results are compared with theoretical calculations done with the Talys 1.8 code.

where N_γ is the integrated number of counts of a given γ peak from the spectrum, Ω is the solid angle, N_p is the number of protons incident on the target, ε_{det} is the detector's efficiency, ρ_x is the areal density of the target, A is the atomic mass, f is the atomic mass scaling factor (we had a composite target - SiO_2) and finally d is the dead time correction factor.

These cross sections had to be corrected for count rate losses due to dead time. The dead time correction factor was calculated assuming that the real and detected rates both follow Poisson distributions. Starting from these assumptions one can prove that the arriving time intervals (Δt) of the registered events are distributed exponentially. Finally, the count rate losses (due to dead time) were calculated as the integral of Δt's exponential distribution with the integration limits from zero up to the dead time value (τ). This integral corresponds to all the incoming events that had arriving times smaller than the dead time value (τ) and, therefore, were lost. Depending on the value of the counting rate, the dead time correction was between 3–6%. In consequence, inserting this correction factor (d) in Eq. (1) an increase of typically 5–20 mb of the differential cross section was generated. For more details regarding the dead time correction procedure used in our experiment see Ref. [20].

The differential cross section was determined at two special angles (i.e., 110° and 150°). These angles were chosen so that the integration procedure of the differential cross section be as precisely as possible. The cosine functions of the two angles mention above are the nodes of the 4th order Legendre polynomials (for details of the integration procedure see Refs. [21–23]). After obtaining the differential cross sections corresponding to each γ transition for the 110° and 150° angles, the total γ production cross section was calculated by integration using:

$$\sigma(E_k) = 2\pi \left[w_{110^\circ} \frac{d\sigma}{d\Omega}(110^\circ, E_k) + w_{150^\circ} \frac{d\sigma}{d\Omega}(150^\circ, E_k) \right] \tag{2}$$

where E_k is the incident proton energy and $\frac{d\sigma}{d\Omega}(110^\circ, E_k)$ and $\frac{d\sigma}{d\Omega}(150^\circ, E_k)$ are the differential cross sections of Eq. (1). The w_{110° and w_{150° coefficients have the values of 1.30429 and 0.69571, respectively, and were calculated by solving the system of equations resulted from a series expansion of the differential cross section in the Legendre polynomials algebraic basis.

Regarding the errors calculation we mention that we considered error propagation coming only from the areal density (ρ_x), γ peaks integration (N_γ) and detector's efficiencies (ϵ_{det}); these quantities had relative errors of 1%, 2% and 3%, respectively.

5. Results and discussions

We were able to extract the absolute γ production cross sections for the most intense transitions, both in ^{16}O and ^{28}Si. Here on all the values for the incident proton energy are given in the laboratory reference frame and they are the mean values calculated using the uniform probability distribution function.

The second excited level in ^{16}O with E_{level} = 6129.89 keV and $J^\pi = 3^-$ decays to the ground state through a E3 γ ray with E_γ = 6128.63 keV. Figure 3 plots the γ production cross section for this transition. In the same figure the experimental results are compared with the theoretical calculations done with the Talys 1.8 code [24] using the default parameters. The main thing to notice here is that our value for the cross section corresponding to an incident proton energy E_p = 12.19 MeV has a much lower value than the one given by Talys. The calculation code overestimates our results but overall the agreement is reasonably good.

The first excited level in ^{28}Si with E_{level} = 1779.03 keV and $J^\pi = 2^+$ decays to the ground state through a E2 γ ray with E_γ = 1778.969 keV. Figure 4 displays the γ production cross section for the first transition in ^{28}Si. In the 4.27–11.13 MeV energy range the agreement between our results and the theoretical calculation is good. After 11.13 MeV, Talys shows a contribution in the cross section which is not confirmed by our data.

6. Conclusions

Using the 9 MV Tandem facility of IFIN-HH, Bucharest and an experimental setup composed of two HPGe detectors, we were able to measure the γ production cross sections for the most intense transitions from ^{16}O and

^{28}Si. The two most important experimental particularities in our experiment were the fact that dead time corrections were needed and, also, the detectors' efficiency had to be extrapolated to very high γ energies. First, we determined the differential cross section at two special chosen angles (i.e., 110° and 150°). Then, using a combination between Gaussian quadrature method and Legendre polynomials series expansion of the differential cross section, the integrated cross section was calculated. The results for the mentioned γ transitions were plotted and compared with Talys 1.8 theoretical calculations. Overall the agreement between the two is reasonably good. In a future paper all these results will be extensively discussed and compared with the corresponding $(n, n'\gamma)$ experiment's cross section data.

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