Nuclear Instruments and Methods in Physics Research B 381 (2016) 110–113

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Cross sections for proton induced high energy γ-ray emission (PIGE) in reaction $^{19}F(p,\alpha\gamma)^{16}O$ at incident proton energies between 1.5 and 4 MeV

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ARTICLE INFO

Article history:
Received 23 February 2016
Received in revised form 30 May 2016
Accepted 6 June 2016
Available online 11 June 2016

Keywords:
PIGE
Nuclear reactions
Fluorine
Oxygen
Cross section

ABSTRACT

We have studied the high energy gamma-rays produced in the reaction $^{19}F(p,\alpha\gamma)^{16}O$ for incident proton energies from 1.5 to 4.0 MeV over NaF/Ag and CaF_2/Ag thin targets in two different sets of data. Gamma-rays were detected with a High Purity Ge detector with an angle of 130° with respect to the beam axis. The cross-sections for the high energy gamma-rays of 6.129, 6.915 and 7.115 MeV have been measured for the whole group between 5 and 7.2 MeV with accuracy better than 10%. A new energy range was covered and more points are included in the cross-sections data base expanding the existing set of data. Results are in agreement with previous measurements in similar conditions.

1. Introduction

Particle-induced gamma-ray emission (PIGE) is a common technique used to detect and analyze elements lighter than calcium [1]. In particular, the analysis of monoenergetic photons from the reaction $^{19}F(p,\alpha\gamma)^{16}O$ can offer applications to the analysis of fluorine concentrations, for example, in dental studies [2,3]. Thus, a precise understanding of that reaction is very convenient.

The $^{19}F(p,\alpha\gamma)^{16}O$ reaction has a *Q*-value of 8.11 MeV and proceeds via the ^{20}Ne nucleus, whose α-decay leads to the first excited states of ^{16}O. A simplified levels scheme of ^{16}O illustrating how the reaction proceeds mainly through the compound nucleus ^{20}Ne is shown in Fig. 1. Three of these excited states (1^-, 2^+ and 3^-) de-excite to the ground state (0^+) emitting gamma rays with energies of 6.129, 6.915 and 7.115 MeV. Besides, the fifth excited state of 8.872 MeV can be also populated and can de-excite to the 1^- and 3^- lower states by the emission of 1.755 and 2.741 MeV photons respectively.

The present work deals with the measurement and analysis of gamma-ray yields and cross-section of the reaction $^{19}F(p,\alpha\gamma)^{16}O$ measured at a polar angle of 130°, ranging the proton beam energy from 1.5 to 4.0 MeV. The final cross-section is calculated for the whole group of high energy gammas, from 5 to 7.2 MeV, and compared with other results from the literature in similar conditions [4–7]. The cross-section values in the beam range of 1.5 and 3.0 MeV are given for the first time.

2. Experiment

The experimental work was carried out at the IST-CTN Tandem accelerator in Lisbon [8], in two separate stages. Proton beam energy was calibrated by the 872 keV resonance of the $^{19}F(p,\alpha\gamma)^{16}O$ reaction, by the 1645 keV and 1930 keV resonances of the $^{23}Na(p,p'\gamma)^{23}Na$ reaction and by the 3470 keV resonance of the $^{16}O(p,p)^{16}O$ reaction [9]. In the first stage, the measurements were performed with a proton beam at energies from 2.51 to 4.04 MeV with an approximate 4 keV step. The proton beam

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http://dx.doi.org/10.1016/j.nimb.2016.06.003
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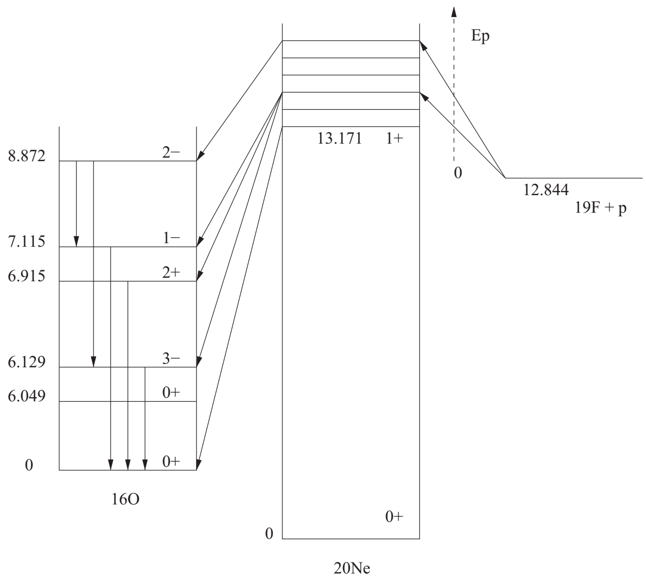

Fig. 1. ^{16}O energy levels scheme. Only gamma emission transitions in excited ^{16}O states are drawn. Transitions from ^{20}Ne to ^{16}O happen via α-particle emission. All energy values are given in MeV. Drawing not to scale.

reached the reaction point with a 2 mm diameter spot after collimators with typical currents of about 100 nA in the reaction chamber, working the last as a Faraday cup. The target consisted on a NaF thin film of 36 $\mu g/cm^2$ evaporated over a self-supporting Ag film of 64 $\mu g/cm^2$. During the second stage, a proton beam energy range from 1.50 to 2.48 MeV was covered in approximate steps of 10 keV with the same accelerator conditions. In the second stage, the target consisted on a CaF_2 thin film of 64 $\mu g/cm^2$ evaporated also over a self-supporting Ag film of 68 $\mu g/cm^2$. Both targets were locally developed by our group in Lisbon.

The gamma radiation was detected with an ORTEC High-Purity Germanium detector (HPGe) of 64 $\times$ 62.6 mm with resolution of 1.76 keV and intrinsic relative efficiency of 45% for the 1.33 MeV ^{60}Co line. It was placed at an angle of 130° and a distance of 55.5 mm with respect to the interaction point. For detecting charged particles, two Camberra Passivated Implanted Planar Silicon (PIPS) detectors of 50 mm^2 each, effective depth of 100 μm, and 26 keV resolution for alphas of 5486 keV from ^{241}Am, were also operative inside the reaction chamber placed at about 110° and 140° with respect to the target. Fig. 2 shows the experimental arrangement inside the reaction chamber.

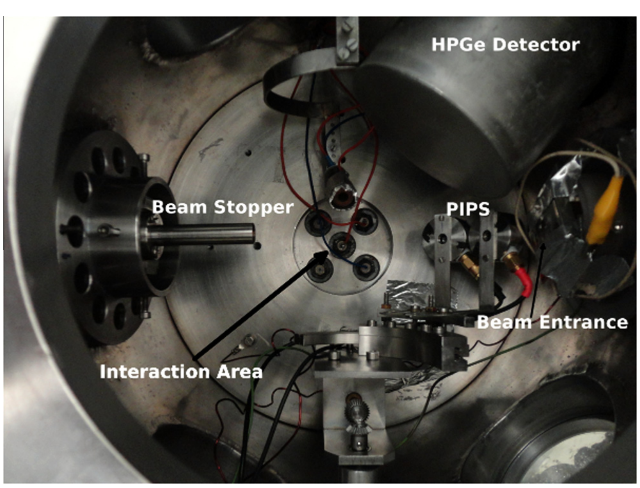

Fig. 2. Photograph of the experimental arrangement inside the reaction chamber. The High-Purity Ge Detector is located at an angle of 130° with respect to the beam line, and a distance of 55.5 mm with respect to the interaction point. The PIPS detectors and their rotating system are also visible. The targets are attached to the chamber's cap.

In the first stage of the measurements, each spectrum was acquired to the same number of total counts, resulting in about 10^5 counts in average in the region of 5 to 7.2 MeV, while a new current integrator was used in the second stage which allowed to record each spectrum to the same number of current collected in the reaction chamber. This method made simpler the normalization procedure for the second set of data.

A custom made current integrator was used for the start/stop DAQ signal so that each spectrum was recorded with the same collected charge in the reaction chamber.

3. Simulation

The reaction chamber's HPGe detector setup was simulated in Geant4 [10] and data was analyzed with ROOT [11], all together within an user-friendly framework for nuclear reactions simulations called EnsarRoot [12], based on the FairRoot framework [13]. The detector geometry was designed to fit all the manufacturer's specifications.

The corresponding spectra of the photons of interest was simulated in the HPGe detector, with the corresponding intrinsic resolution. The kinematics of the reaction was included as well in the simulation, allowing to the photons to be emitted with a random Lorentz boost ranging from $\beta = 0$ to $\beta = 0.02$, as they can escape with the recoil nucleus either at rest or still moving, and in any direction with respect to the beam axis. This results in the effect of having a broadening in the 6.9 MeV and 7.1 MeV photopeaks, together with their corresponding single and double escape peaks. A comparative between an experimental and a simulated spectrum can be observed in Fig. 3.

It is known that the contribution of each peak to the total spectrum changes as the proton beam energy changes [4]. This was included in the simulation by giving individual weights to the sum of the three simulated transitions spectra and fitting that weights to the corresponding real spectrum by a Least Square Method. Results of the individual contributions are shown in Fig. 4. The comparison with data from [4] is also shown.

The main contribution of the simulation to this analysis is a much better estimation and understanding of the detector efficiency at higher energies. The detection efficiency was calculated in simulation for the photon energy range between 4.5 and 7.5 MeV, and a parameterization of the detector efficiency as a function of the energy of the registered photon, $\varepsilon_\gamma(E_\gamma)$, was obtained. The efficiency was then compared with that at high energies extrapolated from measurements with radioactive sources resulting in a good agreement. Our region of interest (5 MeV to 7.2 MeV) falls in the tail of the efficiency curve [14], but the value over the region is far to be constant. Furthermore, a difference of 20% is observed between both ends of the range. By assuming a constant efficiency in the range like the average value, as it is done in [5], the final emission yield of a given photopeak, and therefore the cross-section, can be underestimated by a factor up to 5%. In this work, the parameterization $\varepsilon_\gamma(E_\gamma)$ was applied bin by bin to each acquired spectrum to obtain the yield and the resulting contribution was used for the cross section calculation.