Nuclear Instruments and Methods in Physics Research B 293 (2012) 16–20

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research B

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

K X-ray production cross sections in aluminium for 15, 20 and 25 keV protons

S.J.C. do Carmo [a,b,c,*], F.I.G.M. Borges [c], A.M.F. Trindade [c], C.A.N. Conde [c]

[a] ICNAS, Instituto de Ciências Nucleares Aplicadas à Saúde, Universidade de Coimbra, 3000-584 Coimbra, Portugal
[b] IBILI, Instituto Biomédico de Investigação de Luz e Imagem, Universidade de Coimbra, 3000-584 Coimbra, Portugal
[c] LIP Coimbra, Departamento de Física, Universidade de Coimbra, 3004-516 Coimbra, Portugal

ARTICLE INFO

Article history:
Received 11 July 2012
Received in revised form 25 September 2012
Available online 23 October 2012

Keywords:
PIXE
LE-PIXE
X-ray production cross section
Soft X-rays
Low-energy protons

ABSTRACT

A low-energy particle accelerator has been used to determine experimentally low-energy X-ray production cross sections through the irradiation of thick targets with ions with energies up to 25 keV/ion charge by measuring thick target yields. We obtained aluminium K- X-ray production cross sections values of 8.4×10^{-4}, 1.3×10^{-3} and 1.8×10^{-3} barn for 15, 20 and 25 keV protons, respectively. Although there are no results in the literature for such low-energy impinging protons for comparison, the results presented here are in good agreement with the general trend exhibited for higher energy ranges.

1. Introduction

Particle-Induced X-ray Emission (PIXE) is an analytical technique used for determining quantitatively trace-elements concentrations with an enviable sensitivity [1,2]. This multi-elemental analysis tool was shown to be particularly well suited in a large number of applications in various fields ranging from archeology to biology, medicine and environmental sciences [3–7].

Among these applications, we can point out the analysis of surfaces of solids, by using low-velocity ions due to their reduced range (down to hundreds of nanometers) [8]. However, for this particular purpose, the lack of reliable X-ray production cross sections for low-velocity impinging particles limits the accuracy of such low-energy PIXE analysis. Indeed, although a number of experimentally obtained X-ray cross sections are available in the literature, for the most common impinging particle species (alpha particles and protons) with energies of 1–3 MeV/ion-charge and for the most common targets, the X-ray production cross sections typically used are approximate values calculated from theoretical models with an uncertainty above 10%. The situation is even worse when considering low-energy (tens of keV) incident particles since the experimental data available in the literature is scarce or even nonexistent and the cross sections predicted by the theoretical models differ widely in this low-energy range [8–11]. The accuracy in the characterization of material surfaces through the PIXE technique by using low-energy impinging particles is therefore greatly limited by the lack of this data in the literature, as pointed out by Lapicki [12]. We believe that the reason for this lack of available results is mainly due to the experimental difficulties associated with the detection of the very low X-ray yields resulting from the interaction of the incident particles with the target, since for these low energies the X-ray production cross sections involved are much lower than those for impinging particles in the 1–4 MeV energy range [2].

Nevertheless, since the knowledge of X-ray production cross sections for low energy ions (below 100–200 keV/ion charge) is required in many applications, we decided to determine these for light-ions with energies from 10–25 keV impinging on light elements, making use of the recently built low-energy particle accelerator at the Physics Department of the University of Coimbra, in Portugal [13,14]. Besides, we focused our interest in target elements of low atomic number Z_T, for which the data in the literature is even scarcer. In this case, the lack of accurate data results also from the additional difficulties encountered in the detection of the resultant low-energy characteristic X-rays (i.e. below 1–3 keV) since these X-ray energies are near, or even below, the detectable energy threshold of the semiconductor based X-ray detectors typically used with the PIXE technique. For this energy range and for large detection areas, the Gas Proportional Scintillation Counter (GPSC) type has a better performance than solid state detectors and for this reason we used a detector of this type, optimized for this application [15].

As already mentioned, for impinging ion energies below 100 keV, data in the literature available for comparison is scarce

* Corresponding author at: ICNAS, Instituto de Ciências Nucleares Aplicadas à Saúde, Universidade de Coimbra, 3000-584 Coimbra, Portugal.
E-mail address: sergiocarmo@uc.pt (S.J.C. do Carmo).

0168-583X/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.nimb.2012.09.019

or even nonexistent, the few exceptions being the works of Basbas et al. [16], Szegedi et al. [17] and Khan and Potter [18], that present results for thick aluminium and/or copper targets irradiated with protons with energies down to 25, 40 and 60 keV, respectively. Still, the values presented in [16] are not absolute X-ray yield measurements but results normalized to the value presented by Khan and Potter [18] for 100 keV protons.

In the following sections we describe the experimental set-up and present the results obtained for the X-ray production cross sections in aluminium (Al) targets irradiated with protons with energies from 10 to 45 keV. A comparison of the results obtained with published data is also made.

2. Experimental set-up

To make the X-ray fluorescence measurements, a PIXE experimental set-up was developed based on the recently built low-energy particle accelerator. This accelerator can be divided essentially in three parts, namely the ion source (model IG20 from HIDEN [19] together with a home-made Wien filter having constant magnetic field and variable electric field), the accelerating tube and the reaction chamber.

The gas is introduced in the ion source through a precision needle valve and its ions are produced by impact of electrons, released from a filament through thermionic effect, with the gas molecules. These ions are focused and directed towards the Wien filter, placed at the output of the ion source, where they are selected, entering the accelerating tube only ions of a selected charge to mass ratio. Both the ion source and the Wien filter are kept at a floating high voltage potential using an electronic module supplied by rechargeable batteries and electrically isolated from the reaction chamber by the accelerating tube. This tube consists of insulating glass rings that separate 4 metallic field rings with equal voltage drop between each other. This voltage drop is established by connecting the metallic rings through resistors of high ohmic value (165 MΩ). The upper ring is electrically connected to the ion source, so remains at a high voltage, while the lower ring is connected to the reaction chamber and therefore is at ground potential. The sample holder containing the targets and the X-ray detection system are placed in the reaction chamber which consists of a cylindrical vacuum vessel connected to both the accelerating tube and to a vacuum system. It has several vacuum sealed ports for the different radiation detectors and other devices.

Since conventional Si(Li) detectors were not suitable to detect the low-energy fluorescence X-rays for this particular application, due to both their small radiation window and high detectable energy threshold, an alternative X-ray detector with a large detection area and an improved detection efficiency was used since small cross section values and low-energy X-rays (*K*-lines below 3 keV for elements lighter than Ar and down to C) were expected. An X-ray detection system based on a low-energy Gas Scintillation Proportional Counter (GPSC) was used since such detectors already proved to have a performance even better than low-energy Ge type detectors for X-rays below 2 keV [20]. This GPSC was projected and assembled in our group and optimized for this particular application by minimizing the target-to-detector distance and by maximizing both its active detection area and efficiency [15,21,22]. We also decided to fill this detector with Ar–Xe mixtures, rather than with pure Xe, since this detection media is more suited for the detection of low-energy X-rays, as described in [15,22].

3. Experimental results

After testing and calibrating the experimental system, namely the particle accelerator, the Wien ion selector, the X-ray detector and the data processing system, the PIXE experiments were carried out by bombarding several thick samples with protons in the 10–45 keV energy range. The irradiation of thick targets allows an indirect calculation of X-ray production cross sections, $\sigma(E_p)$, through the experimental determination of the thick target yield curve, $I(E_p)$, defined as the number of X-rays produced in a thick target per impinging proton of initial energy E_p. The advantages are that the target thickness is not an important issue and almost no sample preparation is necessary, avoiding this way several practical difficulties. However, the energy of the ions interacting with the target atoms is no longer constant throughout the target and the X-rays registered in the detector result from the interaction of protons with different energies with the target atoms. As a result, the following relationship was used to obtain $\sigma(E_p)$, given the values of $I(E_p)$ and $dI(E_p)/dE_p$ for each energy E_p and considering that the angles between the incident beam and the specimen surface and between the specimen surface and the detector axis direction are the same and equal to 45° (which was the geometry in our case) [16,23]:

$$\sigma[E_p] = \frac{1}{n}\left[\frac{dI(E_p)}{dE_p}S(E_p) + \frac{\mu}{\rho}I(E_p)\right] \quad (1)$$

where n is the number of target atoms per gram ($n = N_{AV}/A_Z$, where N_{AV} is the Avogadrós number and A_Z is the mass number of the target atoms with atomic number Z, $n = 2.23 \times 10^{22}$ atoms/g for aluminium), $S(E_p)$ the target stopping power at energy E_p (in keV cm^2/g), μ is the target absorption coefficient for the *K*-line considered and ρ is the density of the target ($\mu/\rho = 390$ cm^2/g for the *K*-line in aluminium [16,18]).

The $I(E_p)$ values for different ion energies were obtained by measuring the number of X-ray photons produced in the sample for a known number of impinging ions. The number N of X-ray photons produced in the sample was calculated by fitting the X-ray PIXE spectra, acquired with the GPSC, to Gaussian curves and counting the number of events below the peak that corresponds to the X-ray line of the bombarded sample. The solid angle subtended by the detector and the detector efficiency were also considered in these calculations. The integrated charge of the ion beam was measured directly on the bombarded sample, which was electrically isolated and connected to an electrometer.

Fig. 1 shows a typical spectrum obtained with the GPSC when an Al thick target (31 mm in diameter) was bombarded with protons with energies in the 10–45 keV range. A peak is clearly seen that was identified as being from the Al *K*-line.

The results for the thick target X-ray yields, $I(E_p)$, obtained for Al bombarded with protons of energy E_p in the 10–45 keV range are

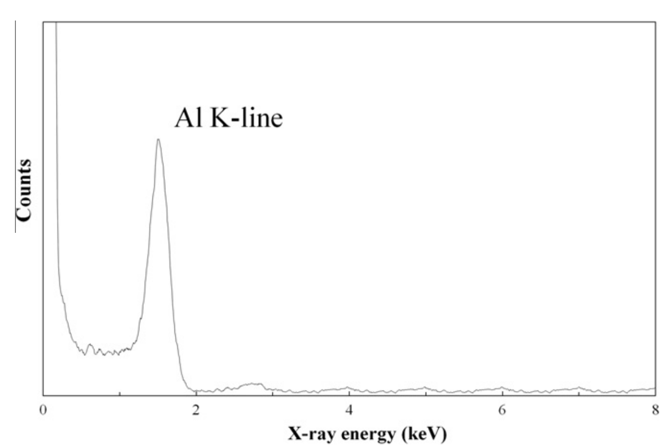

Fig. 1. PIXE spectrum obtained by irradiating an Al thick target with 40 keV protons.