Nuclear Instruments and Methods in Physics Research B 269 (2011) 2011–2016

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

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

Proton elastic scattering differential cross-sections for ^{12}C

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ARTICLE INFO

Article history:
Received 29 April 2011
Received in revised form 30 May 2011
Available online 17 June 2011

Keywords:
Proton elastic backscattering spectroscopy
Carbon
Cross-section
R-matrix

ABSTRACT

Carbon depth profiling presents a strong analytical challenge for all the major ion beam analysis (IBA) techniques, with elastic backscattering spectroscopy (EBS) being widely implemented. In the past, the $^{12}C(p,p)^{12}C$ reaction has been successfully evaluated for proton beam energies up to 4.5 MeV. Currently, an attempt is being made to extend this evaluation to higher energies, namely up to $E_{p,lab}$ = 7 MeV. There is a certain lack of available and/or coherent datasets in literature for these relatively high proton beam energies at backward angles, suitable for IBA. Moreover, the few existing datasets are in certain cases discrepant. Thus, in the present work, the differential cross-section of proton elastic scattering on carbon were measured between 140°and 170°, in steps of 10°, for the proton beam energy range between 2.7 and 7 MeV. The experimental results obtained, along with data from literature, were evaluated applying nuclear physics models. The evaluated results were benchmarked using a thick, mirror polished glassy carbon target at different beam energies and detector angles.

1. Introduction

Carbon is the fourth most abundant element in nature, and its importance in science and technology is critical. It is the main constituent in organic and organometallic compounds and alloys. Either in its pure form, as graphite and diamond, or through its presence in the various forms of plastics (polymers), carbides, fibers, and glasses, it is widely used in the chemical and semiconductor industry as well as, in metallurgy. Thus, the accurate quantitative determination of carbon depth profiles in heavy and light matrices or substrates is of great importance, especially in those cases where the total carbon concentration is relatively low. However, the determination of the carbon distribution, especially on heavy substrates and/or in the presence of other light elements, presents a strong analytical challenge for all ion beam analysis (IBA) techniques. Among others, the $^{12}C(d,p_0)^{13}C$ reaction and the $^{12}C(p,p_0)^{12}C$elastic scattering have been proposed, and they seem to be the most suitable for analytical purposes, owing mainly to the high cross-sections involved, the capability of least destructive depth profiling, and the possibility of probing greater depths inside the targets with the use of a very light ion beam. The elastic backscattering spectroscopy (EBS) is generally preferred in most applications, due to its superior depth resolution, resulting from the enhanced stopping power of the outgoing particle for the same analyzing depth. Moreover, as EBS is an extension of Rutherford backscattering spectroscopy (RBS), and is usually performed in the same experimental setup, with minimal changes of the experimental conditions (beam energy, detector angle and/or thickness), it is the most widely used IBA method for light element depth profiling. More specifically, natural carbon consists of 98.93% ^{12}C and 1.07% ^{13}C. Thus, as far as EBS is concerned, the analytical study of natural carbon is practically equivalent to the study of the main isotope, ^{12}C. On the other hand, as far as differential cross-section measurements are involved, this implies that the use of isotopically enriched targets is not required.

Indeed, EBS can be considered as a well established IBA technique nowadays. The creation of IBANDL (http://www-nds.iaea.org/ibandl/), an especially designed library supported by IAEA, which contains differential cross-sections suitable for IBA that can be directly incorporated in widely used analytical programs, has significantly enhanced the analytical power of EBS. However, the most reliable cross-sections are the theoretically evaluated differential cross-sections. For the most important light elements, the evaluation has already been performed [1]. The evaluated datasets are made available to the scientific community through the on-line calculator SigmaCalc (http://www-nds.iaea.org/sigmacalc/) and through IBANDL. It has to be noted, however, that the theoretical evaluation is a dynamical process, as calculations strongly depend on the quality and availability of experimental differential cross-section data over a wide range of energies and detector angles. Moreover, the validity of the

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doi:10.1016/j.nimb.2011.06.002

evaluated datasets must be benchmarked, using quality thick targets in high-accuracy experiments.

In the case of the $^{12}C(p,p_0)^{12}C$ reaction, a successful evaluation already exists for proton beam energies up to 4.5 MeV [2]. However, in certain applications (study of art objects, glasses, pigments, sediments, etc.) larger penetration depths are required. Nevertheless, above this beam energy, there is a certain lack of available and/or coherent datasets in literature suitable for IBA. Moreover, the few existing datasets [3–11] are in certain cases discrepant. Thus, in the present work, in an attempt to clarify the situation, the differential cross-sections of proton elastic scattering on carbon were measured between 140° and 170°, in steps of 10°, for the proton beam energy range between 2.7 and 7 MeV, with a variable energy step. The experimental results thus obtained, along with data from literature, were evaluated using nuclear physics models. The evaluated results were verified through a benchmark measurement, using a thick, mirror polished glassy carbon target at different beam energies and detector angles. As a result, this new, extended evaluation for proton elastic scattering on carbon for beam energies up to 7 MeV is now already present in IBANDL and SigmaCalc.

2. Experimental setup and procedure

The experiments were performed using the proton beam of the 5.5 MV TN11 Tandem Accelerator of N.C.S.R. "Demokritos", Athens, Greece. The protons, accelerated to $E_{p,lab}$ = 2700–7000 keV in variable energy steps, were led to a cylindrical scattering chamber of large dimensions ($R \sim 40$ cm).The final ion energy of the proton beam was determined by Nuclear Magnetic Resonance (NMR) with an estimated ripple of ~0.1–0.15%, as verified by the 991.89 keV resonance of the $^{27}Al(p,\gamma)$ reaction at the beginning and long after the end of the experiment, using a HPGe detector. It should be noted here that possible significant non-linear deviations of the magnet at higher proton beam energies were not examined in the present work, but in principle they cannot be excluded (although they have not been observed in the past). For this reason, the value of the ripple was slightly overestimated, as to partially account for such effects.

The target was placed at a distance of ~25–35 cm from the detectors. Orthogonal slits ($\sim 4.5 \times 8$ mm^2) were placed in front of the detectors in order to reduce the angular uncertainty (~±1°), while allowing an adequate effective solid angle to be subtended by the detectors. Small cylindrical tubes, variable in length (3–7 cm.) and having a diameter of ~1.1 cm, were placed in front of the detectors in order to avoid any possible excessive background under the carbon elastic peaks due to multiple scattering in the chamber walls and/or in the Faraday cup. With this setup the observed background under the carbon peak was significantly less than 1% over the whole energy range studied, as evidenced in the example of Fig. 1.

The detection system consisted of four Si surface barrier detectors (thickness: 1000 μm; set at 10° intervals) along with the corresponding electronics. The spectra from all four detectors were simultaneously recorded and the procedure was repeated for every $E_{p,lab}$. The beam spot size was $2.5 \times .5$ mm^2, while the current on the target did not exceed ~80 nA during all the measurements. Two liquid nitrogen traps were set on both ends of the scattering chamber in order to reduce the carbon build-up on the target, while the vacuum was kept constant, as low as $\sim 5 \times 10^{-7}$ Torr. Since the problem of carbon build-up on a carbon target may critically affect the results, the following procedure was adopted: The beam spot position was not changed in order to monitor the changes in the target thickness by repeating the measurements after large time intervals, at selected beam energies. The change

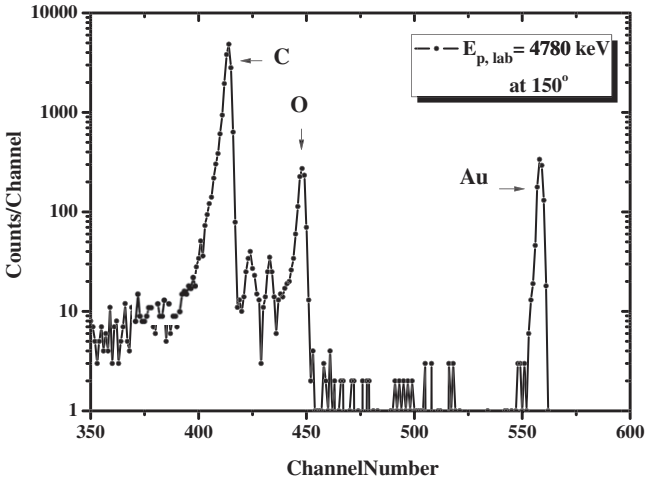

Fig. 1. Experimental spectrum taken at 150° and $E_{p,lab}$ = 4780 keV, along with the corresponding peak identification.

in the ratio of recorded yields caused by the carbon build-up at the location of the beam spot demonstrated a linear increase with time. It was found to be ~9% between the beginning and the end of the experiment. Thus, the integrated counts from the elastic carbon peak were corrected according to the acquisition time of the experimental spectra.

The effective solid angle subtended by the detectors was determined via a 81.1 nCi triple α-source ($^{241}Am/^{239}Pu/^{244}Cm$, IAEA certified, at 4% accuracy), placed at the exact location of the beam spot (and being of approximately the same size).

Two different algorithms were implemented for peak fitting/integration and background subtraction, yielding results within 1–2%, while SIMNRA (v. 6.4) was used for the analysis of the EBS spectra in the benchmarking phase [12]. In order to calculate the mean proton beam energy at half the target's thickness, as well as its additional uncertainty due to energy straggling, Monte–Carlo simulations were performed using SRIM2010 [13]. Ziegler–Biersack–Littmark [14] stopping power data for protons were implemented, as incorporated in both algorithms.

The target consisted of a thin carbon foil of 52 ± 2 μg/cm^2 (according to the specifications for a typical accelerator stripping foil) and a thin gold layer of 14 ± 1 μg/cm^2 that was evaporated on top of it. The thickness of the gold layer was determined by performing X-ray fluorescence (XRF) analysis using the *in situ* developed portable XRF setup. A typical experimental spectrum taken at 150° and $E_{p,lab}$ = 4780 keV is presented in Fig. 1, along with the corresponding peak identification.

3. Data analysis

The determination of the differential cross-section values was carried out following the formula for relative measurements, that is, by comparing the proton elastic differential cross-section to the corresponding one of the $^{197}Au(p,p_0)$ reaction, for the same scattering angle and accumulated charge, as follows:

$$\left(\frac{d\sigma}{d\Omega}\right)^{C}_{\theta} = \frac{\left(\frac{d\sigma}{d\Omega}\right)^{Au}_{\theta,R} * Y_C * N_{Au}}{Y_{Au} * N_C}$$

where Y generally corresponds to the experimental yield (integrated peak counts), and N to the number of corresponding target atoms (areal density). The cross-section of proton elastic scattering from gold was calculated according to the Rutherford formula over the whole energy range under study.