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Towards calibration and characterization of high-energy beams using charged particle retrodiffusion on a double thin carbon foil system

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ABSTRACT

The cyclotron of the IPNAS-CEA laboratory of the University of Liège (Belgium) has built a new high-energy, high-resolution beam line based on the use of a pair of 90° bending magnets showing a energy resolution of $\Delta E = 1.9 \pm 0.4$ keV comparable to that of electrostatic IBA installations. In the 6–20 MeV energy range the contribution of non-Rutherford events to scattering spectra became important and are not very well known. In order to improve our knowledge in that field, a new vacuum chamber especially dedicated to differential cross-section measurements has been constructed. First results obtained with the new set-up are presented.

1. Introduction

The adaptation and development of set-ups allowing the combination of complementary ion beam analysis techniques has proved to be a fruitful mean to investigate and fully characterize materials in general and seems to be specifically suited for the study of cultural heritage artifacts [1–3]. In order to upgrade and enlarge the analytical possibilities of our actual conventional Particle Induced X-ray Emission (PIXE) and Particle Induced Gamma-ray Emission (PIGE) set-up, a new high-resolution high-energy beam line is under development on the CEA-IPNAS cyclotron facility of the University of Liège (Belgium). On that line, we intend to implement backscattering spectrometry analysing technique at beam energy up to 20 MeV. The use of such high-energy beam presents new challenges because (a) cyclotrons usually deliver beams with poor energy resolution and consequently impairs quality of analysing process and (b) differential cross-sections for elastic backscattering of ions from light nuclei, conditioned more by nuclear interactions rather than electrostatic ones, are not very well known yet in this energy range [4]. In order to improve the beam energy resolution, our 20 MV azimuthal varying field cyclotron was coupled to a Berkeley-type pair of 90° left–right bending magnets forming an achromatic doublet. This arrangement reduces by a factor of 20 down to 1.9 ± 0.4 keV the natural dispersion of our beam [5].

Moreover, for these yet unexploited beams in the 6–20 MeV energy range, new and accurate energy calibration points and their respective energy spread evaluation, are requested. Thus, further investigations of these new magnetically-analysed beams and their characteristics have been performed using a new and original double foil experiment. As incident energy increases, the cross-section of scattered ions, given by simple kinematical *K*-factor [6] at low energy, becomes more and more dependent of nuclear compound nucleus resonance processes and leads to strong interference in diffused particles spectrum. Taking in addition advantage of angular dependence at these energies, our set-up allows energy scanning of particle-producing nuclear resonant events for both energy calibration and beam characterization purposes. Our set-up, that allows energy scanning of nuclear resonant events, is thus well suited for both energy calibration and beam characterization studies.

In the following sections we give a brief description of the interactions and principles involved and exploited and, to illustrate the interest of the set-up, we present the results obtained for two different energy ranges and probing particles.

2. Methodology and experimental set-up

2.1. State of the art

Reproducing excitation functions of well known narrow resonances can gives accurate and absolute energy references. This technic, has been widely used in beam diagnostic and accelerators energy calibration procedures and literature provides a large amount of such events in the 0–6 MeV beam energy range. By this mean a resonant event producing gamma rays has already led to a full and accurate characterization of our ≈3 MeV analysed proton beams [5].

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As cyclotrons were historically, rarely used for IBA, there is a great lack in references to perform beam energy calibration at energies higher than ≈6 MeV and new methodologies to provide such information are needed. Moreover, due to its large beam energy dispersion, a cyclotron has a limited ability to fine tune the incident energy to ensure detection of narrow events and, at high-energy the flux of secondary electrons emission limits the ability to measure precisely the beam current for accurate normalization of the spectra.

2.2. Design of an adapted set-up

Firstly, to meet the required control of the incident beam, our magnetic energy selecting device has been equipped with new Caylar–Drusch Nuclear Magnetic Resonance (NMR) probes ensuring real time and absolute monitoring of the magnetic fields value. An additional alimentation permits fine tuning of incident energy by sweeping slightly second magnet field value and consequently allows fine scanning procedure. The second problem has been solved by an advantageous geometrical configuration: based on the use of two thin carbon foils, separated by 10 mm and tilted at 45°, placed on the beam axis, and of a single surface barrier particle detector, situated at 120 mm of the beam axis, our new set-up allows simultaneous detection of the particles emitted by each foil under two different scattering angles (see Fig. 1). This configuration advantageously eliminates systematic errors that could be induced by using a second detector and unexpected differences in its efficiency and/or energy calibration.

The main underlying interest of this configuration is that by measuring expected Rutherford peak intensity ratios, we eliminate the need of charge integration for spectrum normalization, as most of other experimental uncertainties. Considering first, incident particle mass and energy range of interest, then, corresponding stopping powers and Rutherford *K*-factor calculations, appropriate resonant events are chosen and both targets and detectors crystal thicknesses, collimation and positioning, are adapted to ensure both separation of the two pure Rutherford expected peaks in the diffused particle spectrum and sufficient counting rates. Finally, first by referring to nuclear databases and important late 1960's and 1970's studies on nuclear energy levels, appropriate nuclear events are chosen, and then by using codes implementing basic and well established energy and angle dependent formulae ruling nuclear reaction, expected reactions can be predicted.

A subtle analysis of the spectra allows then observation of other expected nuclear events and corresponding peaks and furtherly, a precise determination of scatter angles or incident beam energy as a unique solution of the system of theoretical equations obtained, can be found.

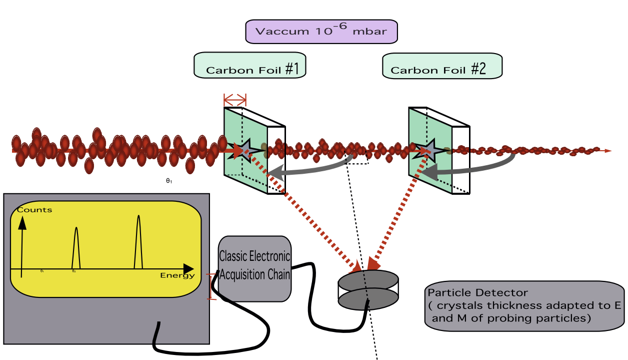

Fig. 1. Schematic description of the set-up allowing simultaneous detection of the particles emitted by each foil under two different scattering angles with a single detector ("double foil experiment").

3. Results

3.1. 6.5 MeV α beam

As a starting point, this double thin foil technique was first carried out to measure the resolution and the energy of an α beam by energy scanning and observing of the narrow resonance ($\Gamma_{cm} = 1.5 \pm 0.064$ keV) of $^{12}C(\alpha,\alpha)^{12}C$ occurring at 6518 keV (lab.) [7,8] and rarely observed or used by this path of deexcitation of compound nucleus ^{16}O. This reaction and its energy range was chosen as 6 MeV alpha beams are of great interest for IBA end-users and to a more specific extent will be a useful first step towards a non-Rutherford cross-section measurement program recently started at the CEA-IPNAS laboratory which requires cross checking results obtained in other partners using electrostatic accelerators able to reach 6 MeV beams. The two natural carbon foils provided by the Arizona Carbon Foil Co. are 20 ± 2 μg/cm^2 thick each and placed in the sample holder in the beam axis. A Canberra partially depleted surface barrier detector, with a 300 μm thick crystal and showing an 11 keV energy resolution on the 5486 keV α-particle emitted by a ^{241}Am source, observes simultaneously the elastic peaks at angles of 88.5° and 95°, respectively. The energy to channel calibration of the electronic chain was conventionally performed by using a ^{241}Am source and a Ortec pulse generator. Mainly due to the angular difference, the two ^{12}C peaks are separated by 269 keV and perfectly resolved (see Fig. 2).

In the first foil, the α beam looses 20 keV, so that an energy scan around 6530 keV beam energy exhibits first an increase of the first foil peak intensity followed, 20 keV later, by an increase of the second foil peak intensity as observed in Fig. 3, where the ratio of the two ^{12}C peak intensities is plotted as a function of the beam energy. This first set of measurements has led to a reliable energy calibration point of our installation for alphas. Let us note that we have eliminated the uncertainty of charge measurement and detector efficiency by measuring peak intensity ratios on a single detector. The large error bars in Fig. 3 reflect the uncertainties on a ratio measurement of two weak lines. Moreover, an estimation of the beam energy spread (a few keV) could be deduced by deconvolution of the excitation curve of the resonance observed.

Let us note, the presence of two small peaks due to ^{16}O presence in preparation layer of self-supporting carbon foils (Fig. 2). First seen as a drawback, a careful study of predicted behavior of ^{16}O cross-section in the precise energy region scanned, has shown the analytical interest of additional peaks provided by other elements from the target as it allows direct current monitoring and normalization. But this method shows severe limitations as soon as nuclear reactions cross-sections are not well known and cannot be extended to additional elements of any *Z*, neither to other energy ranges. We have decided to investigate the opportunity of using peaks provided by nuclear excited levels to monitor current and therefore have increased energy and switched to proton beams.

3.2. 14.2 MeV proton beam

In order to get higher energy calibration points, as well as to explore advantages of using additional pure nuclear peaks occurring in diffused spectrum for indirect charge monitoring purposes, we have decided to investigate proton beams in an energy region where Coulombian barrier is clearly overlapped. Therefore we have observed back scattered spectrums induced by an energetic proton beam while energy scanning in the near region of a weak and narrow ($\gamma_{cm} = 1.1 \pm 0.09$ keV) proton $^{12}C(p,p)^{12}C$ resonance occurring at 14230.75 ± 0.20 keV (lab.) [7,9–11]. The two natural carbon foils provided by the Service des Cibles Minces (Orsay-IN2P3) are