Differential cross sections measurements for PIGE applications

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Particle Induced Gamma-ray Emission (PIGE) is a powerful analytical technique that exploits the interactions of rapid (~1-10 MeV) charged particles with nuclei located near a sample surface to determine the composition and structure of the surface regions of solids (from ~ 0 to 50 μm) by measurement of characteristic prompt γ-rays. This technique has been used since the early 1960s for different applications. PIGE can be used as a complementary technique with particle induced X-ray emission (PIXE) for low-Z elements (Z < 15) since in PIXE measurements, contrary to PIGE, X-rays corresponding to these elements are strongly attenuated in the sample and also efficiency of detector for these low energy X-rays is small. PIGE quantitative analysis of thick samples is usually performed by comparing the measured data with those of standard samples with similar composition [1]. If the composition of the sample considerably deviates from that of the standard one, serious errors may arise due to different stopping powers of protons in the matrices of the sample and standard. It is known that reliable values of the cross section data allow the application of PIGE technique for analysis of light elements regardless of the standard sample. This is performed by integrating nuclear reaction cross section along the depth of the sample employing suitable code [2–4].

The primary quantities required are the stopping power and the cross sections of the interactions involved. Whilst work remains to be done on accurate stopping powers, the field is largely catered for by the considerable body of work of Ziegler and co-workers, embodied in the SRIM computer code[5].

The case is quite different for cross sections for nuclear reactions with γ-rays in the exit channel. Although a considerable body of published data exists in the nuclear physics literature, there is no up-to-date, comprehensive compilation specifically dedicated to the IBA community. A number of PIGE cross-section data have already been uploaded to IBANDL (http://www-nds.iaea.org/ibandl) by members of the IBA community.

The purpose of the present research work is to provide reliable PIGE differential cross section data, for the $^{56}Fe(p,p'\gamma)^{56}Fe$ (Ec = 846.8 keV), $^{63}Cu(p,p'\gamma)$ (Ec =669.6 keV) and $^{65}Cu(p,p'\gamma)^{65}Cu$ (Ec =1115.5 keV) reactions in the laboratory energy range of 2-5 MeV.

The experimental work will be carried out at the 3 MV Tandetron™ accelerator system at the ‘‘Horia Hulubei’’National Institute for Physics and Nuclear Engineering – IFIN-HH, Magurele, Romania. The measurements will be carried out at the IBA reaction chamber. The radiation detection is done by using the four standard detectors. Charged particles are detected by two AMETEK type BU-012-050-100 solid state detectors, which are mounted at a fixed (165^0) and movable ($10–150^0$) position with a solid angular acceptance of 1.641 msr and 5.57 msr, respectively. A HPGe gamma ray detector, ORTEC model GEM10P4-70 and a HPGe X-ray detector, ORTEC IGLET-X-06135-S, are positioned symmetrically in the horizontal plane at 45^0 with respect to the beam direction. Various absorbers can be inserted in front of the particle and X-ray detectors. The in-vacuum HPGe X-ray detector can be placed very close to the samples to maximize the solid angle.

Accurate determination of the energy of the particle beam from the accelerator is very important when nuclear cross sections are measured or for accurate depth profiling using narrow resonances. For very accurate energy calibrations it is usually not enough to calibrate the energy at just one point; it is necessary to calibrate over a range of energies, and, possibly over a range of ions that are used.

There are a number of techniques by which a measurement of particle beam energies may be obtained. Two common techniques for calibrating a ion accelerator are the measurement of neutron threshold energies of sharp (p, n) or (α, n) reactions or the use of nuclear (p, γ), (p,αγ) reactions or (α,α) scattering having narrow, well known resonances with large cross sections.

The use of RBS (Rutherford Backscattering Spectrometry) measurements to determine an internal energy calibration offers several advantages, the most obvious being that it is not restricted to discrete resonance energies or thresholds energies but can be used continuously. This technique uses the conventional backscattering spectrometry setup. Two measurements are required. The first are backscattering measurements of two samples. These data defines two linear equations that relate the energy per channel a and the energy intercept b of the system to the beam energy E. The second

measurement is of some positive-Q nuclear reaction or the measurement of the α particles from a radioactive source, at the same gain. We obtain a third linear equation. Variations of this technique have been attempted in some earlier reports [6-10]. In these reports the elastic scattering approach was used to calibrate the accelerator energy scale. Recently, we applied this technique to calibrate the analyzing magnet of the 9 MV Tandem accelerator [11].
The method adopted to calibrate the voltage of the terminal of the 3 MV Tandetron accelerator consists simply of comparing the energies of alpha particles from a radioactive source with the energies of ^{4}He projectiles backscattered into a silicon detector by carbon and gold layers.
The cross section may be derived from the following expression

$$\sigma_{\gamma}(E_0,\theta) = \frac{Y_{\gamma}(E_0,\theta)}{N_p N_T \varepsilon_{abs}(E_{\gamma})}$$

Where $Y_{\gamma}(E_0,\theta)$ is the measured γ-ray yield (i.e. the area of the γ-ray peak) at projectile energy E_0 and γ-ray detection angle θ, N_p is the number of incident projectiles, N_T is the number of target nuclei per square centimetre and $\varepsilon_{abs}(E_{\gamma})$ is the absolute efficiency of the γ-ray detector correspondent to the E_{γ} energy γ-ray line.
The accurate absolute detector efficiency determination is very important, because it is directly reflected in the quality of the extracted cross-section data.
We intend to use ^{152}Eu at the exact position of the target and, also, Monte Carlo simulation to determine the absolute photopeak efficiency of the γ-ray detectors for energies below 3.5 MeV. In order to interpolate and extrapolate from the experimental calibration points, the following fit to the data will be used (beyond the maximum of the efficiency curve):

$$\varepsilon(\gamma) = a + \frac{b}{E} + \frac{c}{E^2} + \frac{d}{E^3}$$

To eliminate systematic and stochastic uncertainties related to the determination of the absolute values of the collected beam charge, we followed the procedure recommended by Abriola et al. [12] by employing a heavy element such as Ag, as part of the target, for normalization of the cross section against Rutherford backscattering from Ag.
For normalization we intend to use Rutherford scattering of the beam particles at backward angles. Then, in relation to the expression given above for the cross section, the product Np N_T may be derived from:

$$N_p N_T = \frac{Y_S(E_0,\beta) r}{d\sigma_{Ruth}\,(E_0,\beta)/d\Omega \times \Omega\varepsilon}$$

where $Y_S(E_0,\beta)$ is the measured scattered projectile yield for the high-Z element on the target (i.e. the area of the scattered projectile peak) measured at projectile energy E_0 and particle detection angle β, $d\sigma_{Ruth}\,(E_0,\beta)/d\Omega$ is the Rutherford cross section for the high-Z element at projectile energy E_0 and particle detection angle β, ε is the intrinsic efficiency of the particle detector (usually ~100%), Ω is the solid angle of particle detection (assumed to be small) and r is the stoichiometric ratio from the analysed light element to the heavy-Z element.
The targets will be prepared by evaporation of natural ^{56}Fe and ^{63,65}Cu onto thin film. RBS measurements with 2 MeV alpha beam will be performed to determine the stoichiometry as well as the thickness of the target layers by simulation of the RBS spectra with the SIMNRA code.
We need 10 days (30 shifts).

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