Design of the Time of Flight ERDA system for 6 MV tandem ion accelerator

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Abstract. At present, the Ion Beam Laboratory MTF STU in Trnava [1] uses the basic Ion Beam Analysis (IBA) methods, namely Rutherford Backscattering Spectrometry (RBS), Particle Induced X-ray Emission (PIXE), in limited extend Nuclear Reaction Analysis (NRA) and Elastic Recoil Detection Analysis with He beam (He ERDA). The development of the Heavy Ion Elastic Recoil Detection Analysis (HI ERDA) system for our laboratory was initiated. The supposed analysing projectiles will be from O to Au with energies ~ 1 MeV/u. HI ERDA is ideal for measuring the depth concentration profiles of all elements lighter than the mass of the primary ions, present in near surface layers in heavy base material. During the HI ERDA experiment, the high energy heavy ions impinge on the sample at an acute angle, atoms of the sample are elastically recoiled, and their energy and mass has to be determined. We have chosen the detection system consisting of the Time of Flight (ToF) telescope in combination with silicon charge particle detectors. Two time gates will be used to acquire the two time stamps. The fast acquisition electronics has to collect the coincidence energy/ToF/yield multi parametric spectra. The proposed ToF ERDA signal processing system consists from combination of analogue nuclear electronics and the fast digital multi-parameter acquisition system. The first draft of the ToF HI ERDA for Trnava IBA laboratory is presented.

1. Introduction

The Ion Beam Laboratory of the Slovak University of Technology (STU) with the 6 MV Tandem Accelerator currently operates experimental end station dedicated for Ion Beam Analysis [1], which is equipped for the basic IBA methods, specifically they are RBS, PIXE, to a certain extend also resonant and non-resonant NRA [2] and He ERDA.

RBS is ideal for determination of heavy elements depth profiles in light substrate, alternatively resonant and non-resonant NRA can measure depth distribution of individual elemental isotopes of light elements (Z < 15) and PIXE is limited to elements heavier then Al.

Determination of light elements like oxygen, carbon or nitrogen in or on heavy substrates which can be found in many compounds is challenging with those listed IBA techniques. RBS has relatively low sensitivity to light elements in heavier matrices. He ERDA enables to determine the depth distribution of hydrogen and its isotopes. NRA can usually determine only one element at the time and the analysis of the other elements has to be obtained by separate subsequent measurements. It can reach an excellent depth resolution and good sensitivity, but the measurements are time consuming even for single radionuclide.
With the increasing development of multi-layer thin microelectronic devices, thin magnetic storage devices, metallized polymers, advanced ceramic materials, and tribo-coatings, etc., there is a rapidly increasing need to measure depth profiles of elements in surface layers from 10 to 1000 nm thickness.

Effective determination of elemental depth profiles of all elements, including light elements can be performed by Heavy Ion Elastic Recoil Detection Analysis. ERDA is a complementary analytical method to RBS. HI ERDA is an effective method for quantitative depth profiling of all elements in the sample surface region simultaneously within a single measurement in just a few minutes [3].

2. Elastic Recoil Detection Analysis
Conventional He ERDA with a primary helium ion beam and HI ERDA - high-energy heavy ion are considered the two main versions of ERDA. A typical detection configuration for He ERDA is the solid state detector (SSD) - e. g. silicon charge particle detector with an absorber foil placed in front of it. The lighter recoiled protons penetrate through the foil to the detector, while the scattered primary He ions are absorbed in the foil.

2.1. HI ERDA
In HI ERDA heavy projectiles at energies typically of tens MeV collide with sample atoms and knock the atoms lighter than the primary ions out of the sample in the forward direction. A velocity as well as energy are measured simultaneously, and mass of recoil particle is identified from the relation between energy and velocity. Since no stopper foil is used, depth resolution is better than in the case of conventional ERDA.

HI ERDA was successfully applied for the first time more than 40 years ago at the University of Montreal Tandem Accelerator for determination of the depth distribution of light elements in heavy materials [4]. In this case the $^{35}$Cl incident ions in energy range from 30 to 40 MeV were chosen to reach an optimum depth resolution.

The acquisition and evaluation of energy spectra of the recoiled atoms is more complex problem. Preferably, it is appropriate to use the primary beam at the energies around 1 MeV/u, where the kinematics of the atom collisions and the scattering cross sections are well known and the stopping powers are near the maximum (which contributes to the high-depth resolution). Typical ions used for HI ERDA are from $^{16}$O through $^{35}$Cl, $^{63}$Cu and $^{79}$Br, $^{127}$I to $^{197}$Au, accelerated at energy from tens, up to few hundreds of MeV. Energies required for these beams are out of reach of many IBA laboratories. [3].

2.2. ERDA detection systems
In HI ERDA experiment the recoiled sample atoms and scattered incident ions can be separated either by their nuclear charge or by their mass. To achieve this separation, various types of ΔE-E detectors, gas ionization chamber (GIC) and TOF telescopes can be used.

In ΔE – E detection system, the energy deposition (or the stopping powers) and the total energy of atoms are detected. It uses the fact that the stopping power of ions scales as Z, so the different elements will slow down at different rates, generating charge carriers. The gas filled chamber can be used as ΔE – E detector, alternatively E can be measured by SSD detector.

Time-of-Flight Elastic Recoil Detection Analysis (ToF ERDA) telescope usually consists of two timing detectors combined with an energy detector, see figure 1. ToF ERDA was developed in the early 1980s for light element profiling [5, 6].

A velocity as well as energy are measured simultaneously. The recoil masses are identified by means of a coincident measurement of the particle velocity and the total energy [7]. A recoils originating from deeper in the sample will have less energy, or correspondingly longer time-of-flight, than recoils from the surface. After evaluation of recorded multi-parameter spectra, the depth profiles of all individual elements present in the sample can be determined.
The timing detectors measure the time-of-flight over a fixed distance. Although only the ToF spectra are used for further depth profile analysis, mostly energy measurement restrict the mass resolution of the whole system.

SSD or GIC detectors are typical alternatives for ions total energy measurement. In both cases their intrinsic resolution limits mass separation below a few MeV recoil energy. Moreover, SSD detectors suffer considerable radiation damage. The energy resolution of the Si charged particle detectors for heavy ions is significantly worse than for light ions like H and He. As SSD detectors start to degrade after about $10^8$ fission fragments/cm$^2$, their lifetime can be considerably limited [8]. The real lifetime of detectors depends also on the experimental conditions and the composition of the analyzed samples. The advantages of SSD detectors are simplicity of handling and operation.

3. ToF ERDA system for STU laboratory

One of the latest installations of the new ToF ERDA telescope was realized at the University of Montreal, where the original telescope was upgraded [9]. In their case the time-of-flight unit consists of two detectors that use a thin carbon membrane and microchannel plates (MCP) to produce the start and stop signals. The time is used to measure the energy with excellent resolution. The timing units were designed by the Jyväskylä group [10]. The main components of the timing units are the 10 mg/cm$^2$ carbon foils; which emits and accelerates the electrons when an ion passes through it; the “toblerone”, which forms electric field-free volume for the electrons; the electrostatic mirror, which reflects the electrons towards the base of the unit; the microchannel plates (MCP), which multiplies the electrons and the anode, which collects the electron signal and produces a fast, ns pulses.

Further processing of these pulses allows to achieve a resolution bellow 200 ps in ToF measurement. The time between the first and second time signal ranges from tens to hundreds of ns. The time measurement depends only on the separation between the timing C foils, delays in the timing detectors and connecting cables, and will not depend on the detected element and detector damage.

On the other hand, semiconductor detectors have an energy ion-depend calibration that depends on the ion, and their resolution worsens with increasing atomic number and they have a problem with pulse height defect (PHD).

3.1. ToF ERDA telescope

Our proposal for STU ToF telescope follows the upgraded Montreal design described above with the SSD detector for the energy of the recoils measurement [9]. The timing detector design will be based on the design by Busch et al. [11], since it offers excellent timing resolution and simplicity of construction.

The HI ToF ERDA system includes the new beaml ine from the switching magnet to the experimental chamber, equipped with the beam monitoring elements and the HI ERDA detection system based on the ToF telescope, see figure 2.
In addition to the ToF telescope another SSD (H) detector, will be used in combination with a stopping foil to monitor the hydrogen, as the detection efficiency of the ToF camera is low for the hydrogen.

3.2. Signal processing

The current collection of data coming from the IBA detectors through NIM ADCs ensures MPA-3 FAST ComTec multi-parameter system. The proposed signal processing of the detection system will combine an analogue front-end electronics with digital multi parameter acquisition system. It will be based on MPA4T FAST ComTec module [12] capable of recording coincident ToF- and energy and also enabling time stamped data acquisition. MPA4T is a combination of a high resolution multi-stop ToF with a multi-parameter data acquisition system. The stop events can be evaluated at a rate of 10 GHz state changes/sec. The system allows to handle up to four NIM ADCs. Multi-parameter spectra can be accumulated in the RAM of the connected PC.

The timing pulses from start/stop detectors will be directed through a timing preamplifier and a timing discriminator to the fast digitizing time inputs, see figure 3. Signal from SSD (E) energy detector and from the SSD (H) detector will after processing by the standard analog nuclear electronics enter ADCs inputs of the multi-parameter MPA4T acquisition module.

FTP4 can directly recognize coincident data from several detector channels and even very complicated trigger conditions can easily be set by the software during data acquisition or post-processing. [13]. Timestamping offers more options for data analysis as coincidence events can be built also in offline analysis. It can be used for fine-tune the coincidence search parameters to minimize the unwanted background.
4. Summary
It is proposed to supplement the existing IBA analytical methods of 6 MV Tandem Accelerator Laboratory by the HI ERDA system. HI ERDA assumes only Coulomb interactions of point charges, the recoiled atoms from the target are directly detected, and there is no significant theoretical difference from RBS. The kinematics in both methods are very similar, as well as the correspondence between the depth and energy loss.

RBS and ERDA are considered to be quantitative depth profiling techniques without standards. The combination of ERDA with standard RBS is a particularly valuable tool. The recoil energy depends strongly on the projectile mass and it is advantageous to use as a heavy ion beam as possible. However, the beam velocity has to remain roughly constant within 0.5-2.0 MeV/u, in order to remain within the Rutherford scattering regime and the main limitation factor is the maximum ion beam energy achievable from an available ion accelerator and the complexity of spectrometers needed for recoil identification [7].

The proposed HI ERDA takes into account the experience from the recently implemented ToF ERDA telescopes. The MPA4T digital multi-parameter acquisition system is considered as one of the most appropriate commercially available system for ToF HI ERDA. It enables ToF with start and 4-channel multi stop signal digitizers with 100 ps timing resolution and a time-stamping multi parameter system with connections of up to 4 or 8 NIM ADC’s [12]. Currently the detailed design of individual sub-assemblies of the ToF ERDA analytical system is solved.

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