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Optimizing the Rutherford Backscattering Spectrometry setup in a nuclear microprobe

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ABSTRACT

Rutherford Backscattering Spectrometry (RBS) as one of the standard techniques of ion beam analysis for non-destructive quantification of film thicknesses and elemental concentrations, in general requires a good mass separation and energy resolution. In nuclear microprobes large solid angles of detection of ~100 msr are necessary to compensate for the comparably low beam current. However, under these conditions geometrical straggling effects cannot be neglected anymore. Therefore, in order to optimize the RBS detection setup, the geometrical straggling was calculated for circular detectors and the noise contributions to the signal generation and amplification analyzed. The analysis shows that an annular RBS detector should be used directly connected to a dedicated in-vacuum preamplifier. In this way, as is demonstrated in this study with preamplifiers based on an Amptek A250 in a very compact, reliable and low-cost package, excellent energy resolutions of (10.6 ± 0.2) keV FWHM can be achieved in 2.29 MeV proton RBS for a 300 mm^2 Canberra PIPS detector mounted under 86 msr solid angle. For smaller detectors even better energy resolutions are obtained, i.e. (5.1 ± 0.2) keV for a 50 mm^2 Canberra PIPS and (5.8 ± 0.2) keV for a Hamamatsu S1223-01 PIN-photodiode detector for 2.29 MeV proton RBS and Scanning Transmission Ion Microscopy, respectively.

1. Introduction

Rutherford Backscattering Spectrometry (RBS) is one of the most powerful methods in ion beam analysis and allows a non-destructive quantification of film thicknesses and elemental concentrations in materials [1]. In general, a good mass separation is desired in RBS analysis. This can be best achieved with magnetic spectrometers [2] which however are large and expensive and typically allow only low solid angles of detection and are therefore not suitable for ion microprobes.

The analysis of lateral inhomogeneous samples which is typically done in nuclear microprobes requires RBS detectors with comparably large solid angles of the order of 100 msr due to the small ion beam currents in the range of some nA. For these large solid angles the geometrical straggling cannot be neglected anymore.

This paper describes the optimization of a simple RBS detector setup based on standard silicon detectors [3] regarding mass/energy resolution. For this purpose, effects from geometrical straggling were analyzed in detail for different detector positions. In addition, the noise contributions from the electronic setup and the statistics of charge generation were calculated and based on these results dedicated in-vacuum preamplifiers developed. In the following sections, the theoretical analysis, the development of the preamplifiers and test measurements done at LIPSION [4] with the final particle detection setups are presented.

2. Optimization of the RBS setup

2.1. Geometrical straggling

Due to the finite solid angle and scan size a range of backscattering angles $\Delta\theta = \theta_{max} - \theta_{min}$ is covered by the RBS detector. For monoenergetic ions backscattered from a specific isotope this corresponds to a broadening of width $\Delta E_{GS} = |E'(\theta_{min}) - E'(\theta_{max})|$ of the detected energies $E'(\theta)$ (see e.g. [5–7]). In this study, not only the width ΔE_{GS} is calculated, but also the exact energy distribution of the ions backscattered on a given element for circular detector geometries taking into account the kinematic factor $K(\theta)$ as well as the backscattering cross section $\sigma(\theta)$ (the details of the calculation can be found in Appendix A). Effects from the finite scan size on the geometrical straggling are neglected.

The amount of straggling depends strongly on the ion energy as well as ion/target combination and is shown in Fig. 1 for 2.25 MeV protons and helium ions backscattered on carbon for a detector with 100 msr solid angle. For carbon which is the lightest element

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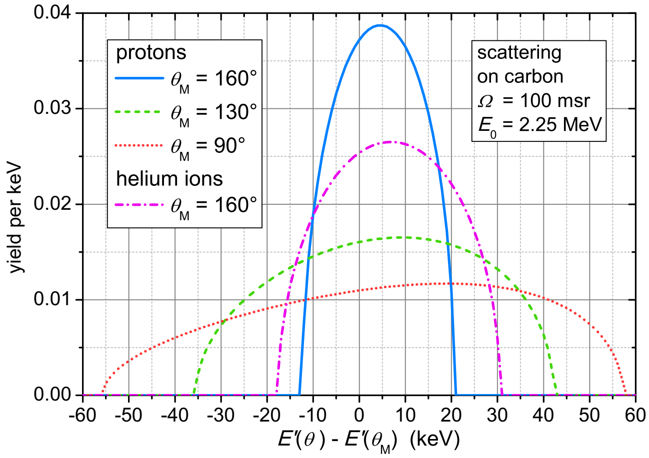

Fig. 1. Straggling expressed as normalized yield per keV for 2.25 MeV protons and helium ions backscattered on carbon and detected by a circular detector mounted under different backscattering angles θ_M.

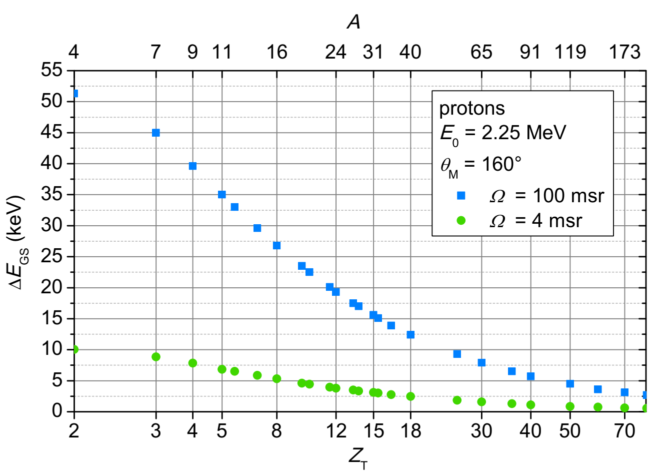

Fig. 2. Broadening ΔE_{GS} of the backscattered energy due to geometrical straggling for 2.25 MeV protons backscattered from different target elements with atomic number Z_T and mass number A under $\theta_M = 160^\circ$ for a solid angle of 100 msr and 4 msr, respectively.

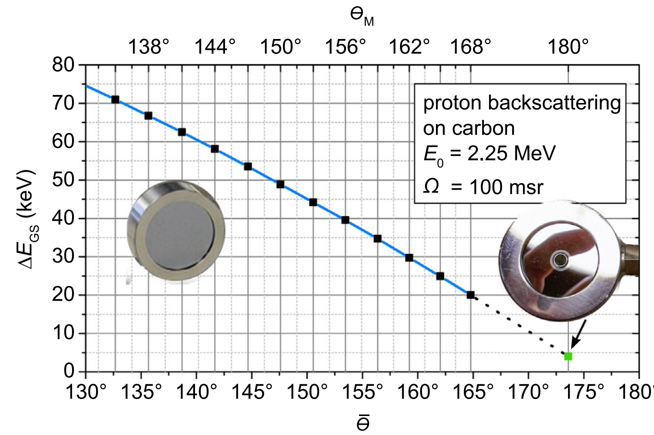

Fig. 3. Width ΔE_{GS} of energy broadening for different detector positions where θ_M denotes the backscattering angle of the center of the detector. In contrast, $\bar{\theta}$ is the angle averaged by the ion yield. The black squares reflect calculations for standard circular detectors, whereas the green square at $\theta_M = 180^\circ$ is the case of the annular detector. The gap in between is the region where a 100 msr detector cuts off the incoming ion beam (dashed line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

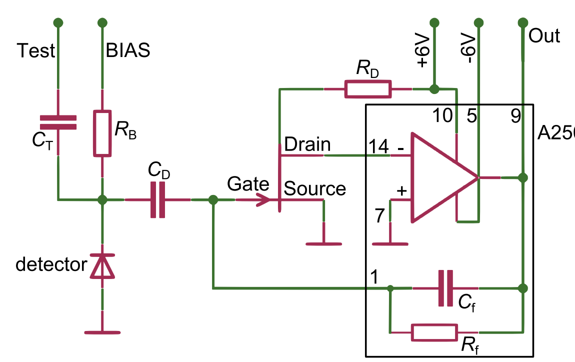

Fig. 4. Circuit diagram of the charge-sensitive preamplifier (noise filters not shown). The components already included in the A250 are displayed within the frame.

that can be expected to occur in substantial amounts in samples the effect is already severe for backscattering angles of $\theta = 160^\circ$ which are not uncommon. In addition to the broadening, there is also a shift of the average backscattering energy compared to $E'(\theta_M)$.

The broadening due to straggling is smaller the heavier the target nucleus and the smaller the solid angle as can be seen in Fig. 2 where ΔE_{GS} is shown as a function of the atomic number Z_T of the target atom for two detectors with 100 msr and 4 msr solid angle, respectively. It also decreases the larger the backscattering angle is (see Fig. 3).

Upon maximizing the backscattering angle, the housing of a standard detector starts to cut off the incoming ion beam. Annular detectors are the solution for this problem. Mounted on 180° backscattering angle, the energy distribution is substantially different from the cases discussed above. Annular detectors cover the whole solid angle for each backscattering angle within a certain range. Therefore, this range is minimal for any given solid angle. The geometrical straggling for a 100 msr detector is so minimized to 4 keV even for proton backscattering on carbon (see Fig. 3). This is small enough compared to the energy resolution of the detector setup due to electronic noise.

2.2. Noise contributions

The signal charge of a detection event is quite small and therefore needs to be amplified for further processing. The final energy resolution of a charged particle detector is influenced by the statistics of the free charge carrier generation, but dominated by the electronic noise of the amplifying system for light ions of several MeV energy. Therefore, for best performance a charge-sensitive preamplifier based on the extremely low-noise operational amplifier A250 from Amptek Inc. was developed. The simplified circuit diagram is shown in Fig. 4. In combination with low-noise FETs, this circuit can be considered as state of the art regarding energy resolution as will be shown in the results section. The testing of several low-noise FETs already revealed good performance for the Sony 2SK152 [8], but the Toshiba 2SK170 [9] gave even better energy resolutions.

In order to optimize the setup the influence of the different noise contributions was analyzed. Most of the contributions are statistical in nature and therefore add up quadratically. The generation of charge carriers, e.g. is liable to statistical fluctuations [10–12].

The following is based on noise analysis that can be found in the literature [13–20]. In the preamplifier the signal from the detector is affected by shot-noise, thermal noise and noise of the FET and