

## Annual Symposium of the Hellenic Nuclear Physics Society

Τόμ. 10 (1999)

HNPS1999



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doi: [10.12681/hnps.2169](https://doi.org/10.12681/hnps.2169)

### Βιβλιογραφική αναφορά:

Vlastou, R., Fokitis, E., Kalliabakos, G., Kokkoris, M., & Kossionides, E. (2019). Characterization of Optical filters using Rutherford Backscattering Spectroscopy. *Annual Symposium of the Hellenic Nuclear Physics Society, 10*, 14–19. <https://doi.org/10.12681/hnps.2169>

# Characterization of Optical filters using Rutherford Backscattering Spectroscopy

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## Abstract

The composition and thickness of optical filters, especially designed for the Auger project, were measured using the RBS method. The aim of this project is to detect the extensive air showers, developed by the interaction of very energetic cosmic rays with the atmospheric air. This swarm of particles, moving at the speed of light through the atmosphere, ionizes the nitrogen atoms, which radiate UV photons in the range of 300-420 nm. This nitrogen fluorescence is subsequently detected by fluorescence detectors having optical filters placed in front of their photomultipliers with high transmittance in the region of 300-420 nm and low transmittance outside this region, in order to maximize the photon signal to background photon ratio.

The required transmittance of the optical filters led to specific production techniques, such as the dielectric multi-layer thin film deposition on a substrate, using high-low index UV-transparent materials. In order to select the optimal deposition technique for the mass production of these filters, the RBS method has been used, among others, to provide information concerning the thickness of the individual layers and possible deviations from the desired stoichiometry. The optical filters presented in this work were made of 6 and 12 thin film layers of  $WO_3/MgF_2$  deposited on UV glass. The samples were bombarded with  $\alpha$ -particles at  $E_\alpha = 3MeV$ , provided by the 5.5 MV Tandem Accelerator at NCSR "Demokritos". The RBS spectra were analyzed utilizing the computer simulation code RUMP.

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## 1 Introduction

The composition and thickness of wide band multilayer optical UV-filters, especially designed for the fluorescence detector of the Auger project [1], have been measured using the RBS method. The aim of the filters is to increase

the signal to noise ratio in detection of nitrogen fluorescence induced in the atmosphere by the highest energy cosmic rays. These cosmic rays interact with the atmospheric air and produce extensive air showers which, in turn, ionize and excite nitrogen atoms. The fluorescence emitted by the nitrogen atoms, molecules and ions is concentrated in the range 300-410 nm. This radiation will be subsequently collected and detected by arrays consisted of spherical mirrors, photomultipliers and optical filters placed in front of them, with their passband matching the nitrogen fluorescence region. The filters passband should match the above nitrogen fluorescence emission region with high transmittance (higher than 85% in average), while the transmittance in the region 410-600 nm should be less than 2%. The filters, being able to maximize the signal to noise ratio, allow the fluorescence detectors to be used during the night, when the moon light produces high levels of background noise [2]. In addition, the maximum possible variation of the optical transmittance, with the angle of the direction of the incident light to the photomultiplier collector, should vary within  $15^\circ$  (in root mean square value) from the axis perpendicular to the filter surface. Finally, the filters should be characterized by uniform spectral properties and mechanical stability for the mass production process.

The required characteristics of the optical filters led to specific production techniques, such as the dielectric multilayer thin film deposition on UV glass, using high-low refractive index combinations of UV-transparent materials, such as  $Al_2O_3$ ,  $Sc_2O_3$ ,  $ZrO_2$ ,  $WO_3$  for high index and  $MgF_2$ ,  $SiO_2$  for low index layers. The appropriate software has been developed for the design of the filters [3], to calculate the optical thickness and combination of layers required for an optimal performance. The main deposition technique, used to produce 1 to 12 layer pairs of the mentioned materials, was electron beam deposition. After the production of specific filters, the RBS method has been used to provide information concerning the relative thickness and homogeneity of the individual layers as well as possible deviations from the desired stoichiometry.

## 2 Experimental technique

For the RBS measurements, a 3.0 MeV alpha beam was used, provided by the tandem T11/25 accelerator at the NRCPS "Demokritos". The detector was Si surface barrier, positioned at  $165^\circ$  with respect to the beam direction and at a distance of 14 cm from the target. The total beam charge was determined by measuring the yield of the beam particles that were elastically scattered by a Au layer of  $8.7 \pm 0.8 \mu g/cm^2$  evaporated on a thin carbon foil of  $15 \mu g/cm^2$  thickness. The foil was placed at the entrance of the chamber and the scattered beam was detected by a silicon surface detector placed at an angle of  $37^\circ$  with respect to the beam direction. The energy loss and the angular spread of the beam passing through the foil were negligible. The data acquisition and control

hardware were driven by a personal computer with the use of the appropriate software.

### 3 Experimental results and discussion

Several filters made of combinations of thin films with  $Al_2O_3$ ,  $Sc_2O_3$ ,  $ZrO_2$ ,  $WO_3$  for high refractive index and  $MgF_2$ ,  $SiO_2$  for low refractive index layers, have been examined by RBS. The spectra were analysed by utilizing the computer code RUMP [4]. Typical results for two of the samples consisted of 6 and 12 pair layers of  $WO_3/MgF_2$  are shown in Figs 1 and 2 and will be discussed in more detail. It is seen that a good fit to the data could be achieved and reliable results could be extracted (with an uncertainty up to 10%) in most samples. The peaks of the heavy element W can be clearly separated by the  $^4He$  beam and can thus be used to determine the relative thickness of the films (by using the nominal density of the bulk materials) as well as their stoichiometry. The Mg and F peaks are sitting on the background of the substrate and can only be analysed by using the additional information coming from the valleys between the heavy element peaks. These valleys correspond to the energy loss of the beam passing through the  $MgF_2$  layers, so their width and depth depend on the thickness and the stoichiometry of the layers.

Concerning the stoichiometry of the thin films, the  $MgF_2$  layers were found to follow the desired composition, while in the  $WO_3$  layers, oxygen losses of up to 15% were observed. These results are consistent with the comments presented in ref. [5].

The optimum calculated thicknesses [3] of each of the high and low index materials, were the same (quarterwave) for each material. However, the thicknesses of the deposited layers were found to vary, due to the instability of the thickness monitor during the deposition process. From the analysis of the RBS spectra, the relative thicknesses of the individual layers exhibit a variation from the average value of the order of 10% for  $WO_3$  and 9 – 16% for  $MgF_2$ .

During the deposition of dielectric materials a reduced packing density of the films can be produced which may affect the film properties [5]. The packing density  $p$  is defined as the ratio of the density of the film material to the bulk material. Since the same mass of the material in a film with reduced packing density, fills a larger volume than a dense film, the geometrical film thickness is enhanced. The hardness, stresses, stability, as well as the optical properties of the films, can also be influenced by the packing density. The refractive index  $n$  of the film is affected by the lower packing density since the voids of the film have an index  $n=1.0$ , while by absorbing water vapors when exposed to

air, the refractive index of the voids becomes  $n=1.33$ .

By using the relative thickness (with the density of the bulk material) of all the layers, extracted from RBS, as well as the total thickness measurement with a step profilometer, the packing density of the deposited layers could be deduced. For both  $MgF_2$  and  $WO_3$  the packing density was found to be  $p = 0.92 \pm 0.09$ . The result of  $WO_3$  is in good agreement with the value presented in ref. [5], while for  $MgF_2$  is higher than that of ref. [5].

#### 4 Summary

RBS has been used as a characterization technique during the development of multilayer thin film optical filters especially designed for the fluorescence detector of the Pierre AUGER Project. Several combinations of films with materials of high refractive index, such as  $ZrO_2$  and  $WO_3$  and low refractive index, such as  $MgF_2$  and  $SiO_2$  have been examined. Two of them are presented in this work, namely samples with 6 and 12 layer pairs of  $WO_3/MgF_2$  films. The relative thickness and the stoichiometry of the individual layers, the thickness variation of the layers, as well as the packing density of materials after the film deposition have been deduced. The extracted values have been compared with the ones taken from the literature. The next step will be to compare the findings of the RBS method with results obtained using spectral transmittance and reflectance, as well as other characterization techniques, such as XRF, in order to propose the optimum filter design technologies.

#### Acknowledgements

It is our pleasure to thank A.Travlos, of Inst. of Materials Science, NRCPS "Demokritos", for preparing the optical multilayer filters and for useful discussions. Our warmest thanks to A. Karydas of Inst. of Nuclear Physics, NRCPS Demokritos, for making the XRF measurements.

Acknowledgements are also due to A.Geranios, A.Petrides and M.Vassiliou of the University of Athens, for measuring the spectral transmittance of the filters.

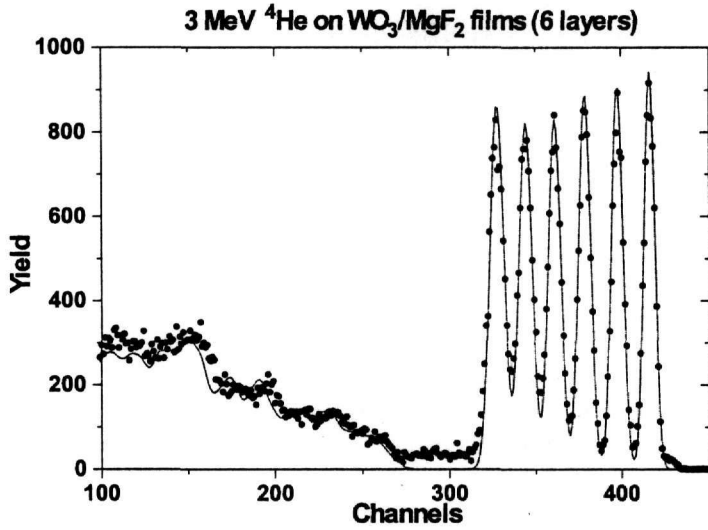


Fig. 1. RBS spectrum of 6 layer pairs of  $\text{WO}_3/\text{MgF}_2$  films on UV glass taken with 3 MeV  $^4\text{He}$ . The 6 strong peaks of W correspond to the 12 layers of  $\text{WO}_3$ . The solid line represents simulation by the RUMP code.

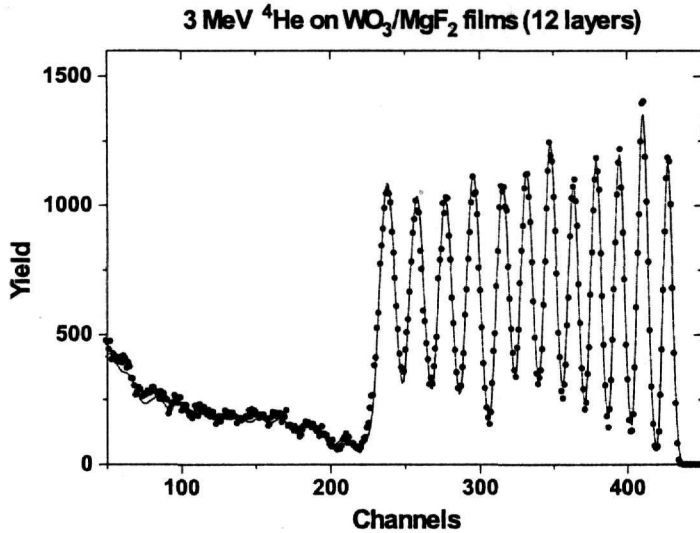


Fig. 2. RBS spectrum of 12 layer pairs of  $\text{WO}_3/\text{MgF}_2$  films on UV glass taken with 3 MeV  $^4\text{He}$ . The 12 strong peaks of W correspond to the 12 layers of  $\text{WO}_3$ . The solid line represents simulation by the RUMP code.

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