Journal of Physics: Conference Series

PAPER • OPEN ACCESS

Enhancement of counting statistics and noise reduction in the forward-scattering detectors on the VESUVIO spectrometer

To cite this article: P Ulpiani *et al* 2018 *J. Phys.: Conf. Ser.* **1055** 012008

IOP Conf. Series: Journal of Physics: Conf. Series **1055** (2018) 012008 doi:10.1088/1742-6596/1055/1/012008

Enhancement of counting statistics and noise reduction in the forward-scattering detectors on the VESUVIO spectrometer

P Ulpiani[a,b], **G Romanelli**[c,b], **L Arcidiacono**[d,b,e], **D Onorati**[f,b], **G Festa**[d,b], **M Krzystyniak**[c], **E Schooneveld**[c], **F Fernandez-Alonso**[c,g], **C Andreani**[f,b,d,h] **and R Senesi**[f,b,d,h]

[a] Università degli studi di Roma Tor Vergata, Dipartimento di Scienze e Tecnologie Chimiche, Via della Ricerca Scientifica 1, Rome, 00133 Italy

[b] Università degli studi di Roma Tor Vergata, Centro NAST, Via della Ricerca Scientifica 1, Rome, 00133 Italy

[c] ISIS Facility, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 OQX, UK

[d] Centro Fermi - Museo Storico della Fisica e Centro Studi e Ricerche "Enrico Fermi", Piazza del Viminale 1, Rome, 00184 Italy

[e] UCL-Institute of Archaeology, University College of London 31-34 Gordon Square London WC1H 0PY United Kingdom

[f] Università degli studi di Roma Tor Vergata, Dipartimento di Fisica, Via della Ricerca Scientifica 1, Rome, 00133 Italy

[g] Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK

[h] CNR-IPCF Sezione di Messina, Viale Ferdinando Stagno d'Alcontres 37, Messina, 98158 Italy

E-mail: `pierfrancesco.ulpiani@uniroma2.it`

Abstract. New evidence of the increased count rate in deep inelastic neutron scattering spectra is provided. Experiments were performed using photon-sensitive yttrium-aluminum-perovskite detectors, installed on the VESUVIO spectrometer at the ISIS pulsed neutron and muon source. At present, these detectors work with a low-level discrimination threshold measuring photons with energy greater than 600 keV in order to avoid background photons from the boron in the beam stop, and other environmental sources. We discuss the advantage in reducing the level of the threshold so as to detect some high-intensity low-energy prompt-gamma rays emitted after the radiative capture of 4.9 eV neutrons by gold, used as energy analyser on the VESUVIO spectrometer. This work shows an improvement of the statistical poissonian error bars and noise on the difference of spectra recorded with and without the energy analyser. The application of such new acquisition strategy discussed here will improve the detection limit of hydrogen atoms in samples, as well as allow a more precise line-shape analysis of nuclear momentum distributions, mentioning just few applications of deep inelastic neutron scattering experiments on VESUVIO.

1. Introduction

The quantitative and non-destructive assessment of hydrogen content in bulk samples is a topic of increasing interest in materials science [1, 2, 3]. Neutrons are the probe of choice for the investigation of the hydrogen dynamics in materials, owing to a higher scattering cross section compared to X-rays. Amongst the many neutron-based techniques, electron-Volt (eV) spectroscopy allows for a direct counting of hydrogen atoms in a sample. For high values of energy and momentum transfer, the spectral response of a system is composed of a mass-resolved collection of peaks which are related to the nuclear momentum distributions of every element in the system [4, 5, 6], with the hydrogen peak being the most intense and the best resolved signal. The described regime is referred to as impulse approximation, and the technique is named Deep Inelastic Neutron Scattering (DINS). The unique information available using epithermal neutrons comes at two costs: first, neutron facilities tend to moderate the probe's energy to maximise the flux in the cold and thermal regions; second, the efficiency of traditional neutron detectors is inversely proportional to the neutron velocity, thus poor for epithermal neutrons. Therefore, bespoken detection strategies need to be identified, and many efforts have been devoted to develop novel detection technologies [7, 8, 9]. The development of pulsed accelerator-driven neutron facilities provided an optimal framework for the development of eV neutron spectroscopy, owing to a substantial epithermal flux as opposed to research reactors. In such cases, inverted- (direct-) geometry instruments select the final (initial) energy of neutrons using an energy analyser, while the initial (final) energy and the energy transfer are calculated using the Time-Of-Flight (TOF) technique. The detection difficulties are overcome by using foils with narrow and intense nuclear resonances by which a neutron with a certain energy is captured and a prompt-gamma ray cascade is emitted and efficiently recorded by gamma-sensitive detectors. In order to be a suitable resonance filter, the material should be easy to handle and characterised by a narrow nuclear resonance at the eV energy isolated from other resonances. Several materials have been discussed in pioneering experiments at the Los Alamos National Laboratory, such as plutonium, rhenium, uranium and gold [10].

VESUVIO is an inverted-geometry spectrometer at the ISIS pulsed neutron and muon source [11, 12], using the gold resonance at ca. 4.9 eV to fix the final energy of scattered neutrons. The former incarnation of the instrument, the eV Spectrometer (EVS), was equipped with foils of ^{238}U, with intense prompt-gamma emission peaks at high energies (4060 keV and 6395 keV [13]). In order to discard the high photon background from boron present in the beam dump at ca. 500 keV, a Low-Level Discrimination Threshold (LLDT) was set to 600 keV.

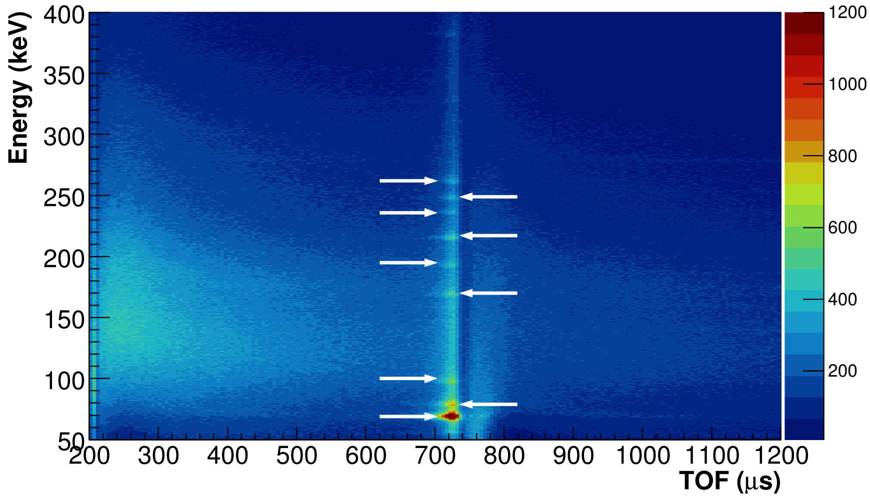

Figure 1: Intensity contour map of γ emission for radiative neutron capture of the gold foil in a bi-parametric (neutron TOF - photon energy) map, reproduced from reference [14]. It is evident the predominance of signal peaks at energies lower than the actual energy threshold of 600 keV at ca. 700 µs which corresponds to the resonant gold capture at 4.9 eV.

Recent time-resolved prompt-gamma activation analysis (T-PGAA) results [14], reported in Figure 1, show how the most intense γ peaks from radiative neutron capture of gold, used at present as energy analyser on VESUVIO, are below the LLDT used, therefore suggesting that a better choice of the threshold could be identified. Our results show that decreasing the threshold there is an improvement in the spectra acquired, therefore demonstrating that the actual energy threshold could be improved for this detection configuration. We present preliminary results about such investigation.

2. Methods

We acquired DINS spectra [4, 15] on VESUVIO from a standard polyethylene sample with a thickness of 0.25 mm. Since 2007, VESUVIO is equipped with photon-sensitive Yttrium-Aluminum-Perovskite (YAP) detectors [16] in forward scattering. Two gold resonant filters are used: one of them is positioned on the detector surface in order to convert neutrons into detectable photons [17], while the second foil can be cycled along (foil in) or away from (foil out) the trajectory between the sample and the detector. The difference of the spectra recorded in the two configurations allows for the subtraction of the environmental gamma-background, in a procedure referred to as Foil Cycling Technique (FCT) [16, 18]. The expression of the count rate, $C(t)$, as a function of TOF t within the impulse approximation and in the assumption of the same background in the foil-in and -out configurations, and after the foil difference is

$$C(t) = 2\left(\frac{2}{m}\right)^{1/2}\frac{E_0^{3/2}}{L_0}I(E_0)A^2(E_1)\eta(LLDT)N_M\sum_M b_M^2\sqrt{\frac{E_1}{E_0}}\frac{M}{\hbar Q}J_M(t)\Delta\Omega, \tag{1}$$

where m is the neutron mass, $I(E_0)dE_0$ is the number of incident neutrons with energy between E_0 and $E_0 + dE_0$ per unit time, $\eta(LLDT)$ is the probability that the γ-ray cascade is detected for a fixed LLDT, A(E_1) is the n-γ conversion efficiency of neutron with energy E_1, N_M is the number of scattering centres with mass M in the sample, $J_M(t)$ is the Neutron Compton profile, b_M the scattering length and $\Delta\Omega$ the solid angle covered by a given detector.

The threshold of five YAP detectors was decreased from the original value $V = 600$ keV operating on the individual detector discriminator card. As the lowest value of the settable threshold $V_0 > 0$ for the discriminator was unknown, the threshold for each detector was set dividing the available range $\Delta V = V - V_0$ in five equal intervals. Table 1 shows the thresholds chosen for used detectors. All measurements were performed both with changed set-up and standard configuration.

Table 1: Threshold chosen for the five used detectors. The available range ΔV, from the lowest energy value V_0 to the actual threshold $V = 600$ keV, was divided in five parts, one for each detector. The detector position is also reported; r is the distance between the sample and detector, θ the polar angle while ϕ is the azimuthal angle.

Detector	Estimated threshold	r $[m]$	θ	ϕ
a	V_0	0.51	52	131
b	V_0 + 20% ΔV	0.50	47	140
c	V_0 + 40% ΔV	0.50	44	151
d	V_0 + 60% ΔV	0.51	41	163
e	V_0 + 80% ΔV	0.52	52	-132

3. Results and Discussion

The spectra acquired with different thresholds were compared in order to quantify the improvement obtained. Figure 2 shows the largest difference in DINS spectra recorded after (red line) and before (black line) the change of the LLDT with a total proton charge of ca. 1530 µAh . The spectra reported for detector a are normalised by the proton change accumulated in the synchrotron. We can see the polyethylene recoil peaks of hydrogen (lower TOF) and carbon (higher TOF). It is evident that lowering the threshold there is a count rate increase, in particular there is about a factor 3 at the hydrogen peak position. This increase is very significant in detector a and it decreases gradually for the other detectors where the modified threshold approaches the original value.

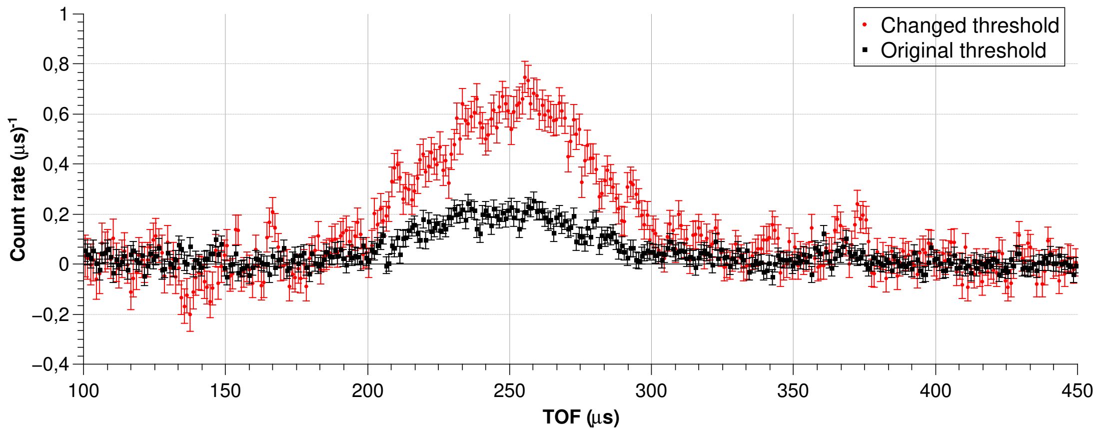

Figure 2: Comparison of polyethylene spectra acquired with original (black line) and changed (red line) threshold from detector a normalized to the proton charge accumulated in the synchrotron. The FCT for signal isolation is used. The peak at lower TOF is associated to hydrogen and the one at higher TOF to carbon. An enhancement of the count rate is evident for the changed configuration compared to the original one.

In order to show the decrease of the relative error bars, it is useful to calculate the ratio

$$\delta(t) = \frac{\text{Relative error bars for changed threshold}}{\text{Relative error bars for original threshold}} = \frac{\Delta_c(t)}{\Delta_o(t)}. \tag{2}$$

As shown in Figure 3 the ratio between relative error bars is qualitatively lower than one for all

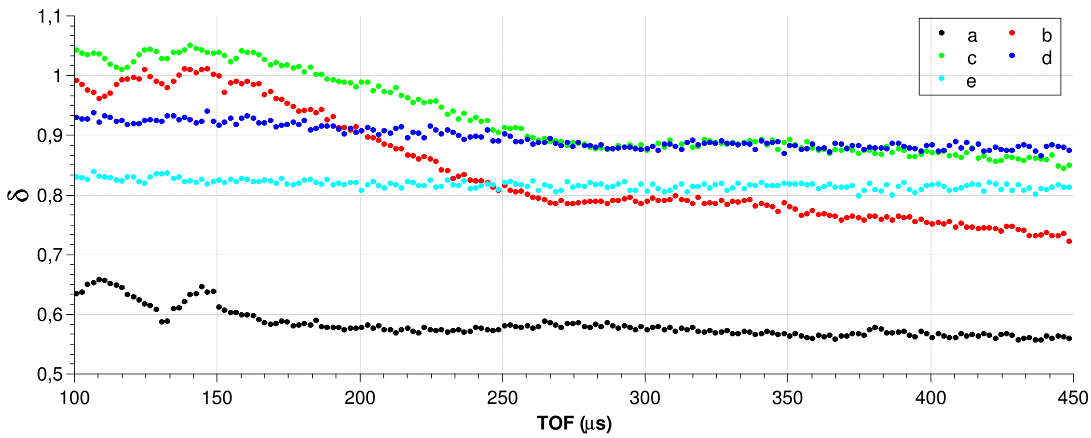

Figure 3: Comparison between the ratio δ for the five different detectors associated to the polyethylene spectra. The ratio represented implies an error bar reduction from 10% (detector c) to more than 40% (detector a).

the five detectors considered. In particular, detector a, d and e show a relatively flat ratio over the TOF range as opposed to detector b and c where the ratio approaches one for low TOF, then decreases and becomes almost constant for TOF larger than 250 μs. The reduction of the relative error bars for TOF higher than 250 μs ranges between 10% for detector d and more than 40% for detector a. The features that one can see between 100 and 150 μs in Figure 3 can be related to the structures of the raw data shown in Figure 4 where the spectra acquired in foil in and out configuration are represented for original and changed threshold of detector b. As we can see even if the background is satisfactorily subtracted through the difference method, the rise of count rate at low TOF for the changed threshold brings to a not-constant δ factor. The decrease of the delta factor is a consequence of the increased number of photons detected as the threshold is lowered. Of all the photons detected, those coming from the neutrons scattered by the sample and captured by the gold foils would contribute to a constant lowering of δ over the entire TOF range, as they would correspond to a constant increase of the signal from neutron Compton profiles. The features of the δ factor at low TOF values therefore suggests that additional environmental background is included in the count rate when the LLDT is lowered. Looking at the TOF where the new background peaks are, we can associate them to the resonant gamma emission from cadmium which covers the forward scattering detectors.

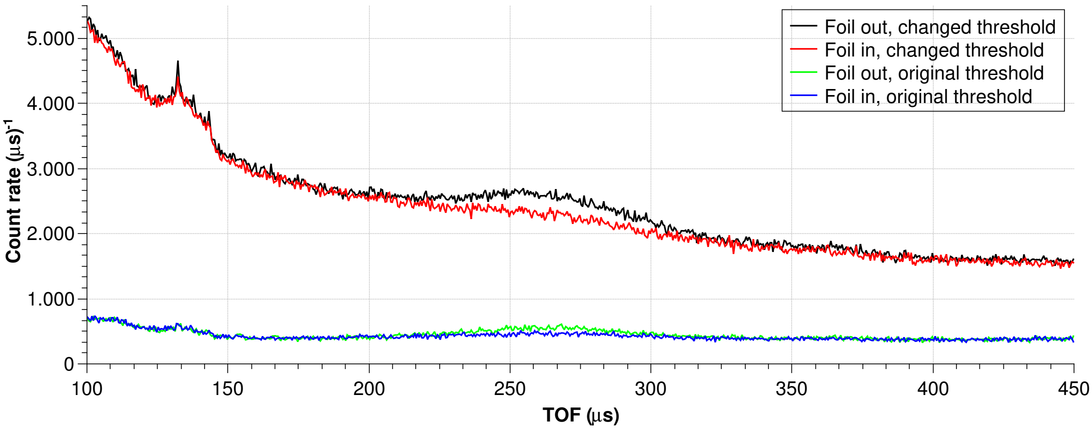

Figure 4: Comparison between the polyethylene spectra acquired in foil in and out configuration with detector b using changed and original threshold. It is evident for low TOF and changed threshold an increase in background counts which is not present for original threshold. It is perfectly subtracted using the difference method.

In addition to the showed decrease in the relative error bars, the change of the LLDT provides a reduction of the noise in DINS spectra. In order to show this, we focus our attention on a certain region of the TOF where there are no neutron Compton profile peaks and the count rate is expected to be vanishing. In this region we calculate the standard deviation σ, around the average value ρ, of the dispersion of count rate $C(t_i)$ for the original and changed setting. The ranges chosen are

$$range\ \ 1: \quad (100 < t < 160)\ \mu s$$

$$range\ \ 2: \quad (390 < t < 450)\ \mu s$$

respectively to the left of the proton peak (range 1) and to the right of the carbon peak (range 2). In the assumption of constant binning, the standard deviation, is calculated as

$$\sigma = \sqrt{\frac{\sum_i (C(t_i) - \rho)^2}{N-1}}, \tag{3}$$

Where i is the bin index and N is the total number of bins in the TOF range analysed. The result for the two ranges is shown in Figure 5 where is represented the ratio $\chi = \dfrac{\sigma_{changed}}{\sigma_{original}}$

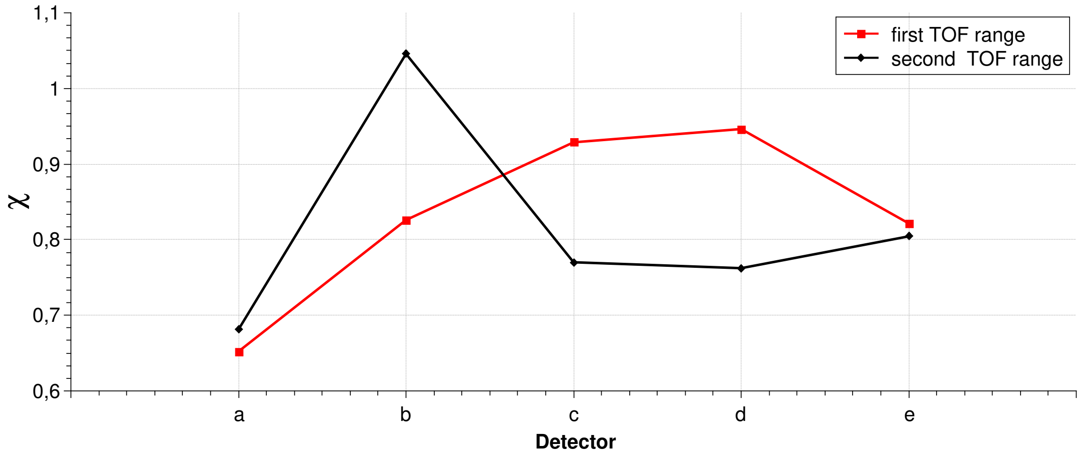

Figure 5: Ratio of the statistical noise $\chi = \frac{\sigma_{changed}}{\sigma_{original}}$ in the first (left of hydrogen peak) and second (right of carbon peak) TOF range. The ratio is smaller than one in the most cases.

for each detector. One can notice how the noise is reduced in the majority of detectors, a particularly relevant result for the analysis of the line-shape of neutron Compton profiles in DINS experiments. The change of the LLDT has brought an increase of the total count rate that is due not only to signal but also to background counts. What is interesting is that the signal to background ratio remains in the same order of magnitude even if the there is an increasing effect in the signal counts. The optimizations showed are reflected also on the physical parameters obtained with DINS experiments. In particular, fitting the hydrogen experimental Neutron Compton profile of polyethylene sample in both the changed and original configurations, we calculated the values of the hydrogen mean kinetic energy $< E_k >$ reported in Table 2. The results are obtained summing all the detectors from a to e to increase the statistics. As we can see the error is decreased by ca. 50% for the changed configuration.

Table 2: Values of hydrogen mean kinetic energy $< E_k >$ in polyethylene obtained fitting the experimental Neutron Compton profile for both changed and original threshold.

	Original configuration (meV)	Changed configuration (meV)
$< E_k >$	148 ± 11	145.2 ± 5.9

4. Outlook and Conclusions

In this work we have shown how the change of the low-level discrimination threshold provides a reduction of the relative statistical error bars and of the noise in deep inelastic neutron scattering experiments which make use of YAP detectors. In particular, the reduction on statistical error bars was found in range between 10 % for small changes of the threshold and 40 % for a nominal removal of the threshold. Further studies will be devoted to evaluate, as acquisition method, an upper level discrimination threshold and its effect on the quality of the spectra acquired detecting only photons with energy lower than 300 keV. Alternatively the implementation of detectors sensitive to low-energy photons such as gas-electron multiplier [19, 20] will be considered. In future investigations, the linearity relation between the LLDT and the photon energy will be tested, and the value of V_0 will be assessed, moreover, the response of a given detector to a change of LLDT due to its electronics will be analysed. Our results show a promising potential for

IOP Conf. Series: Journal of Physics: Conf. Series **1055** (2018) 012008 doi:10.1088/1742-6596/1055/1/012008

VESUVIO science programme, as they can improve the line-shape analysis of neutron Compton profiles [21].

Acknowledgements
This work was partially supported within the CNR-STFC Agreement (2014-2020) concerning collaboration in scientific research at the ISIS pulsed neutron and muon source.
The authors gratefully acknowledge the UK Science & Technology Facilities Council for financial support and access to beam time at the ISIS Facility.

References

[1] Silverwood I P, Parker S F and Catlow C R A 2016 *Physical Chemistry Chemical Physics* **18** 17140–17140
[2] Kaplan D, Sol N, Velasco G and Thomas P 1978 *Applied Physics Letters* **33** 440–442
[3] Philipps V, Wienhold P, Kirschner A and Rubel M 2002 *Vacuum* **67** 399–408
[4] Andreani C, Krzystyniak M, Romanelli G, Senesi R and Fernandez-Alonso F 2017 *Advances in Physics* **66** 1–73
[5] Pietropaolo A and Senesi R 2011 *Physics Reports* **508** 45–90
[6] Tardocchi M, Pietropaolo A, Andreani C, Bracco A, D'Angelo A, Gorini G, Imberti S, Senesi R, Rhodes N and Schooneveld E 2004 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **526** 477–492
[7] Belgya T, Kis Z, Szentmiklósi L, Kasztovszky Z, Festa G, Andreanelli L, De Pascale M, Pietropaolo A, Kudejova P, Schulze R *et al.* 2008 *Journal of Radioanalytical and Nuclear Chemistry* **278** 713–718
[8] Pietropaolo A, Andreani C, Rebai M, Giacomelli L, Gorini G, Cippo E P, Tardocchi M, Fazzi A, Rinati G V, Verona C *et al.* 2011 *EPL (Europhysics Letters)* **92** 68003
[9] Tardocchi M, Gorini G, Pietropaolo A, Andreani C, Senesi R, Rhodes N and Schooneveld E 2004 *Review of scientific instruments* **75** 4880–4890
[10] Brugger R, Taylor A, Olsen C, Goldstone J and Soper A 1984 *Nuclear Instruments and Methods in Physics Research* **221** 393–407
[11] Isis facility website `www.isis.stfc.ac.uk`
[12] Senesi R, Andreani C, Bowden Z, Colognesi D, Degiorgi E, Fielding A, Mayers J, Nardone M, Norris J, Praitano M *et al.* 2000 *Physica B: Condensed Matter* **276** 200–201
[13] Molnar G 2004 *Handbook of Prompt Gamma Activation Analysis*
[14] Onorati D Master's thesis University of Rome Tor Vergata URL `http://purl.org/net/epubs/work/33481015`
[15] Andreani C, Colognesi D, Mayers J, Reiter G and Senesi R 2005 *Advances in Physics* **54** 377–469
[16] Schooneveld E, Mayers J, Rhodes N, Pietropaolo A, Andreani C, Senesi R, Gorini G, Perelli-Cippo E and Tardocchi M 2006 *Review of scientific instruments* **77** 095103
[17] Andreani C, Pietropaolo A, Senesi R, Gorini G, Tardocchi M, Bracco A, Rhodes N and Schooneveld E 2002 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **481** 509–520
[18] Mayers J, Tomkinson J, Abdul-Redah T, Stirling W, Andreani C, Senesi R, Nardone M, Colognesi D and Degiorgi E 2004 *Physica B: Condensed Matter* **350** E659–E662
[19] Sauli F 2016 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **805** 2–24
[20] Kaneko K and Kohmura T 2012 *Journal of Instrumentation* **7** C07001
[21] Ulpiani P Master's thesis University of Rome Tor Vergata URL `https://epubs.stfc.ac.uk/work/35035571`