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Nuclear Instruments and Methods in Physics Research A 579 (2007) 431–436
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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A phoswich well detector for radioxenon monitoring

Wolfgang Hennig[a,*], Hui Tan[a], Anthony Fallu-Labruyere[a], William K. Warburton[a], Justin I. McIntyre[b], Anshel Gleyzer[c]

[a] *XIA LLC, 31057 Genstar Rd, Hayward, CA 94544, USA*
[b] *Pacific Northwest National Laboratory, 902 Battelle Boulevard, Richland, WA 99352, USA*
[c] *PhotoPeak, Inc., 10180 Queens Way No. 3-5, Chagrin Falls, OH 44023, USA*

Abstract

One of several methods used to detect nuclear weapons testing is the monitoring of radioactive xenon in the atmosphere. For high sensitivity, monitoring stations use a complex system of separate beta and gamma detectors to detect beta–gamma coincidences from characteristic radioxenon isotopes in small amounts of xenon extracted from large volumes of air.

We report a simpler approach that uses a single phoswich detector, comprising optically coupled plastic and CsI scintillators to absorb beta particles and gamma rays, respectively, and then detect coincidences by pulse shape analysis of the detector signal. Previous studies with a planar prototype detector have shown that the technique can clearly separate beta only, gamma only and coincidence events, does not degrade the energy resolution, and has an error rate for detecting coincidences of less than 0.1%. In this paper, we will present a new phoswich well detector design, consisting of a 1″ diameter plastic cell enclosed in a 3″ CsI crystal. Based on Monte Carlo modeling and experimental results, the design will be characterized in terms of energy resolution and its ability to separate beta and gamma only, and coincidence events.

PACS: 07.85.Nc; 28.41.Te; 29.40.Mc

Keywords: Phoswich detector; Digital pulse shape analysis; Radioxenon monitoring; Beta–gamma coincidence detection

1. Introduction

Monitoring radioactive xenon in the atmosphere is one of several methods currently employed to detect nuclear weapons testing as part of the Comprehensive Nuclear Test Ban Treaty. A monitoring station, such as the Automated Radioxenon Sampler/Analyzer (ARSA) instrument developed at Pacific Northwest National Laboratory (PNNL) [1], extracts Xe from large volumes of air and then measures its radioactivity in an extremely low background counter. Since the Xe isotopes of interest all emit one or more beta particles or conversion electrons simultaneously with one or more gamma- or X-rays, beta–gamma coincidence is used to suppress the natural background.

Commonly used time-based coincidence detection using separate detectors for beta and gamma radiation requires multiple channels of photomultiplier tubes (PMTs) and readout electronics—in the case of the ARSA system a total number of 12. This leads to complex and bulky systems that requires careful gain matching and calibration. In one approach to simplify the system [2], researchers at PNNL explored the use of a phoswich detector made from two scintillator materials with slow and fast decay times to detect beta and gamma radiation, respectively. The phoswich was read out by a single PMT and rise time analysis was performed to classify interactions as occurring in either or both parts of the detector. This method worked well to distinguish the radiation interacting in any single part of the detector, but radiation interacting in both parts—corresponding to the beta–gamma coincidences required for radioxenon monitoring—could not be easily identified using this algorithm, instrumentation and

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[*] Corresponding author. Tel.: +1 510 401 5760; fax: +1 510 401 5761.
E-mail address: whennig@xia.com (W. Hennig).

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doi:10.1016/j.nima.2007.04.093

particular choice of scintillators, and the authors concluded that it would be nearly impossible to measure the beta and gamma energies separately.

We previously described [3] an improved phoswich detector and pulse shape analysis method to detect beta–gamma coincidences from radioxenon. The phoswich detector consisted of a 1 mm disk of the fast plastic scintillator BC-404 optically coupled to a 25.4 mm long cylinder of the slow scintillator CsI(Tl). Beta particles and conversion electrons are absorbed primarily in the plastic, while longer range gamma rays and X-rays are absorbed primarily in the CsI. Using several novel DSP strategies to process the waveforms acquired from this planar phoswich detector, we showed that the technique clearly separated beta only, gamma only and coincidence events, measured the energy deposited in each part of the detector without degrading energy resolution, and had an error rate for detecting coincidences of less than 0.1%.

The planar phoswich detector described above has a low-coincidence detection efficiency due to its geometry: at least half of all gamma and beta radiation from the source does not interact with the detector. In this paper, we present a new phoswich well detector design with significantly improved detection efficiency, consisting of a hollow cylinder of BC-404 (holding the Xe) embedded in a larger cylinder of CsI. Several design options are studied through simulations of light collection and evaluated for ease of manufacturing, and preliminary results of a first prototype well detector's performance are shown.

2. Phoswich well detector design

The geometry of the well detector has the following design constraints: (i) to contain the volume of a typical radioxenon sample, the diameter of the plastic cell should be 25.4 mm; (ii) according to radiation transport simulations described in Ref. [3], in order to stop all beta radiation but not absorb a significant amount of X-rays or gamma rays, its wall thickness should be 2.5 mm; (iii) to absorb most of the X-rays and gamma rays, the cell must be surrounded by $\sim$25.4 mm of CsI on all sides. These constraints can be met with a variety of detector designs. The designs studied so far in detail are shown in Fig. 1: (a) a planar geometry as used in the initial experiments, (b) a spherical cell with a vertical split, (c) a cylindrical cell with a 1″ plug, and (d) a cylindrical cell with a horizontal split.

Fig. 2 shows the results of Monte Carlo light collection simulations (using DETECT2000) for these geometries, assuming an index of refraction of 1.50 for the PMT glass window and the optical couplant, 1.58 for the BC-404 and 1.85 for the CsI. The variation of light collection efficiency causes different amounts of light to be collected for gamma rays of the same incident energy interacting in different locations of the detector. Weighting the light collection efficiency according to the volume each point represents (i.e., in first approximation, the probability of interaction), we obtain an estimate of the contribution of the light collection non-uniformity to the broadening of peaks in the energy spectrum. The probability distributions for each simulated detector are shown in Fig. 3 and the peak resolutions are listed in Table 1. Note that the light collection non-uniformity is only one contribution to the overall energy resolution of the detector, adding in quadrature to contributions from other effects such as photostatistics, crystal non-uniformities and energy non-linearities, to a typical value of $\sim$17% for characteristic 80 keV gamma rays emitted from radioxenon. As long as the changes in the light collection efficiency due to the embedded cell or the crystal geometry are minor, the energy resolution of the detector will thus not worsen significantly. Furthermore taking into account of the ease of manufacturing, we arrive at the following conclusions for the feasibility of these designs.

Geometry (a) is very easy to manufacture and has the most uniform light collection since it is a homogenous CsI crystal (2.4% full-width at half-maximum (FWHM) at

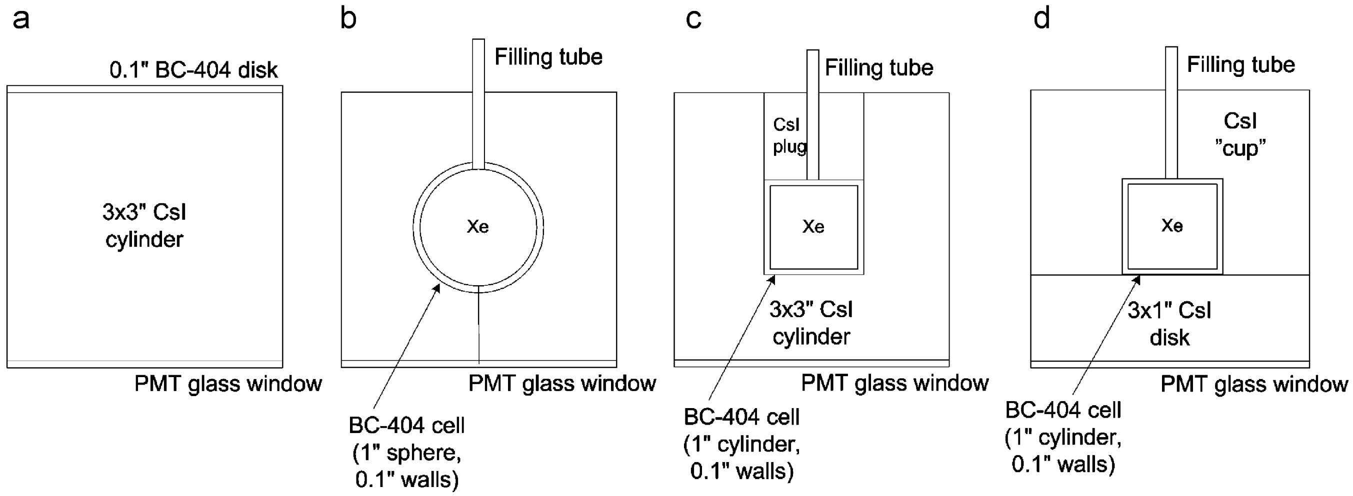

Fig. 1. Geometries of detector designs studied. All outer surfaces have diffuse reflective coating, all interfaces between CsI and BC-404 or CsI and CsI have optical couplant.

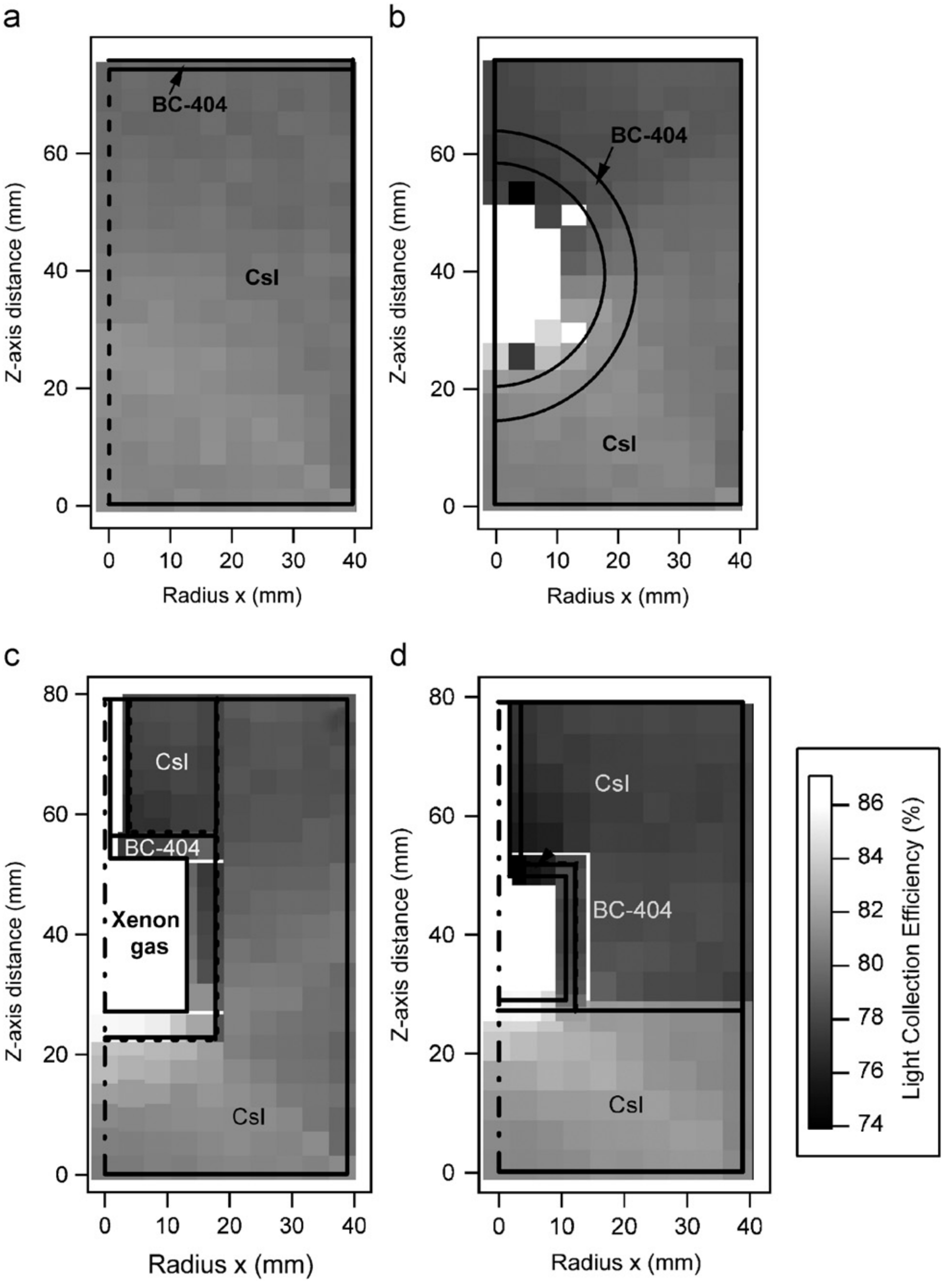

Fig. 2. Geometric distribution of light collection efficiency for outer reflection coefficients = 0.95. By symmetry, only half of the crystal is simulated (from radius $x = 0$–38 mm). All figures use the color scale in (d).

RC = 0.95). However, due to its low-coincidence detection efficiency, it is not suitable for radioxenon monitoring applications, and here only serves as a comparison for the other geometries. Geometry (b) has the best light collection efficiency of the well detectors (2.9%), since the vertical boundary between the crystal halves is not an obstacle for the light to reach the PMT. However, in practice it was considered too difficult to machine the CsI crystal into the shapes required. Geometry (c) has only a small volume from which light is collected inefficiently (the plug above the cell) and therefore still reaches good energy resolution (3.8%), but while the components can in principle be machined, in practice air will be trapped below the cell during assembly, thus obstructing the light collection from the BC-404. The horizontal crystal boundary in geometry (d) makes light collection from the upper detector portion significantly less efficient, resulting in double peaks in the probability distribution with a total width of ~5%. However, since during assembly air can escape through the filling tube, geometry (d) is also significantly easier to manufacture and assemble, and it was subsequently built as the first prototype of the well detector. Experiments to quantify the penalties of the less uniform light collection of design (d) are under way and further geometries are studied for future prototypes.

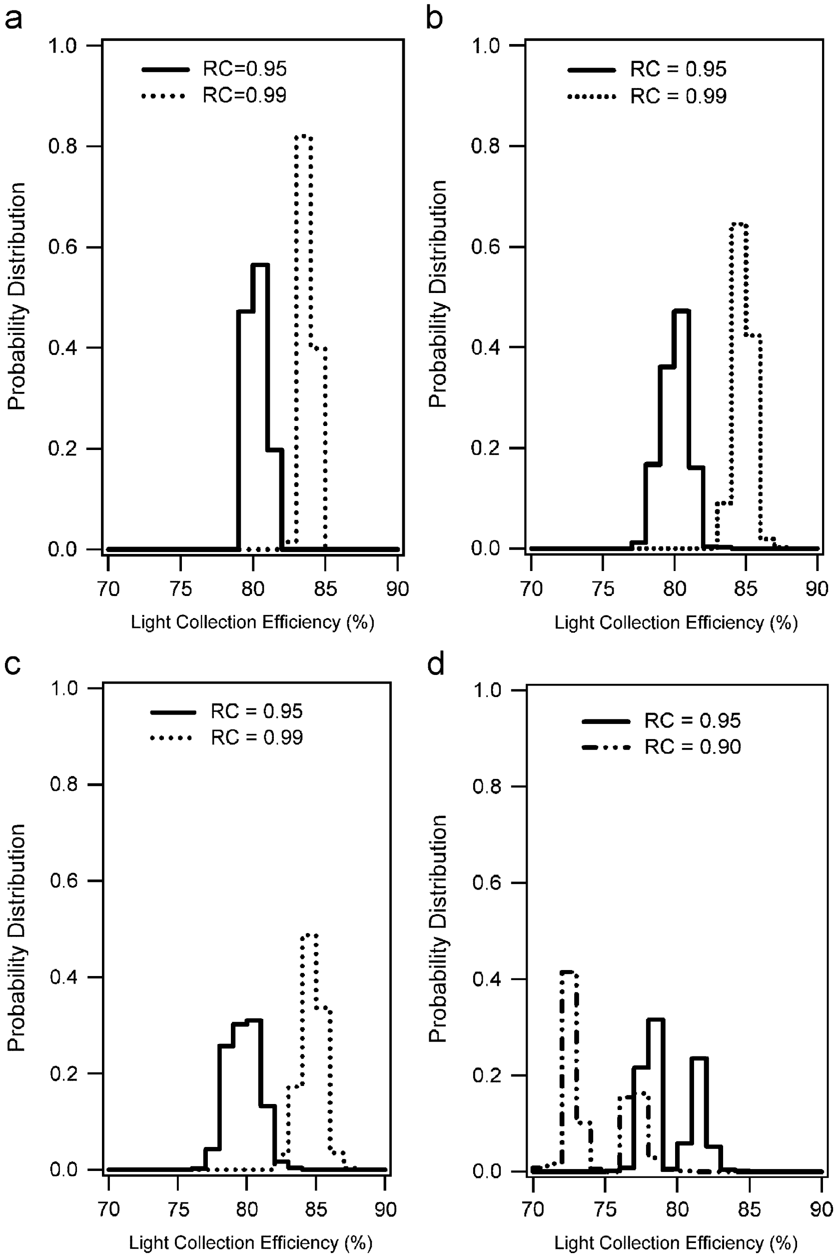

Fig. 3. Volume-weighted efficiency.

Table 1
Resolutions due to light collection

Detector	dE/E (RC = 0.99) (%)	dE/E (RC = 0.95) (%)	dE/E (RC = 0.90) (%)
(a)	1.3	2.4	—
(b)	1.8	2.9	—
(c)	2.3	3.8	—
(d)	—	~5	~6

3. Preliminary results

The prototype detector (geometry d) was tested first with a ^{137}Cs needle source inserted into the detector through the filling tube and secondly with a ^{222}Rn emanation source (NIST SRM 4974). The ^{222}Rn source was placed into a container connected to the filling tube and the ^{222}Rn gas gradually diffused into the detector. The PMT was read out with a DGF Pixie-4 [4] that also calculated filter sums for further offline analysis. In the analysis, pulses were classified as (1) CsI only, (2) plastic only, and (3) combination pulses (see Fig. 4) and their energy contributions in each part of the detector was calculated.

The events acquired from the ^{222}Rn source can then be displayed in a 2D energy scatter plot (Fig. 5) in which beta–gamma coincidences form horizontal bands of events with constant gamma energy and varying beta energy,

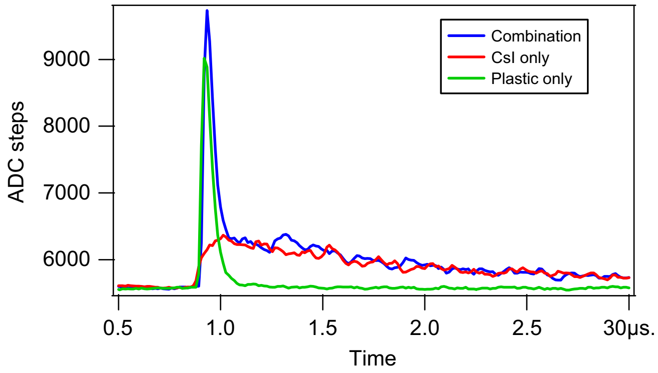

Fig. 4. Waveforms from phoswich detector.

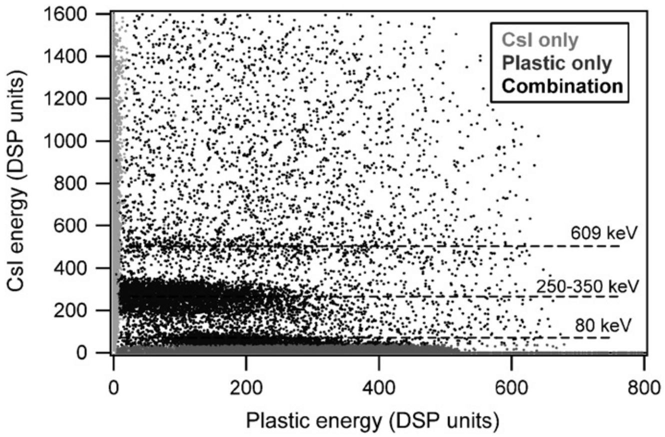

Fig. 5. 2D energy scatter plot from ^{222}Rn.

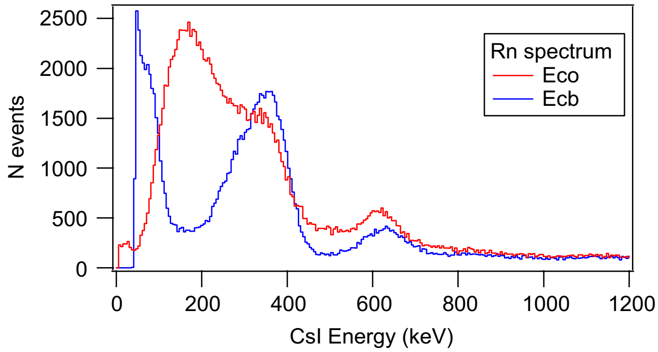

Fig. 6. Histogram of energy deposited in CsI for CsI only events (E_{co}) and combination events (E_{cb}).

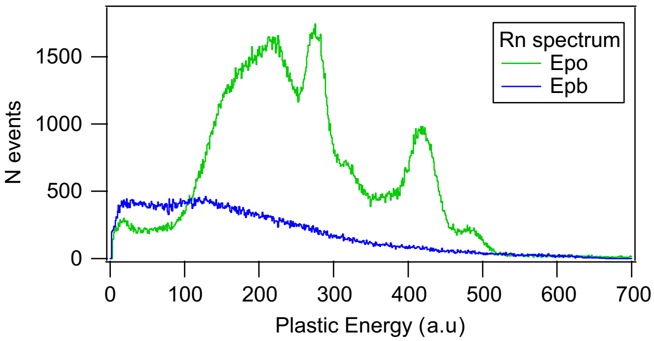

Fig. 7. Histogram of energy deposited in BC-404 for plastic only events (E_{po}) and combination events (E_{pb}).

corresponding to the 609, 240–350 keV (multiple lines) and ~80 keV lines from the ^{222}Rn decay chain.

Figs. 6 and 7 show the individual histograms for energies deposited in the CsI and the BC-404 for each event type. Note that in the CsI spectrum, at energies around 170 keV, the counts for coincident events are reduced by more than a factor of 6 compared to CsI only events, demonstrating the suppression of non-coinicident background events. In these preliminary measurements, the resolution at 609 keV is 19.7% for CsI only events and 17.4% for coincidence events. In the measurements with ^{137}Cs, there are no beta–gamma coincidences, and the resolution for the 662 keV peak for CsI only events is 15.0%. Compared to typically ~7% resolution at 662 keV obtained with the planar phoswich detector in Ref. [3], the resolution of the well detector is notably degraded. In future work, we will therefore optimize the preliminary setup to eliminate any other degrading factors (e.g., electronic noise), determine how much of this degradation is due to the non-uniformity of light collection discussed above and how significant it will be in the energy range of interest for radioxeneon ($<=250$ keV). In addition, the algorithms will be refined to improve the separation of coincidence events from plastic only events for energies below 80 keV.

4. Summary

In conclusion, a prototype phoswich well detector has been designed, modeled and manufactured. Preliminary test results using radioactive sources were presented. While the effects of crystal non-uniformity on the light collection in the detector and their possible limitations for the achievable energy resolution have to be studied further, preliminary measurements show that the detector is capable of detecting beta–gamma coincidences and separately measuring the energy deposited in each part of the detector. The prototype phoswich well detector will be used to further test the technology and to refine the pulse shape algorithms for better separation of event types. The final detector design based on these results will then be combined with designated readout electronics to create a replacement module for existing ARSA detector and readout electronics.

Acknowledgment

This work was supported by the US Department of Energy under Award no. DE-FG02-04ER84121.

References

[1] J.I. McIntyre, K.H. Abel, T.W. Bowyer, J.C. Hayes, T.R. Heimbigner, M.E. Panisko, P.L. Reeder, R.C. Thompson, J. Radioanal. Nucl. Chem. 248 (3) (2001) 629.

[2] J.H. Ely, C.E. Aalseth, J.I. McIntyre, J. Radioanal. Nucl. Chem. 263 (1) (2005) 245.

[3] W. Hennig, H. Tan, W.K. Warburton, J.I. McIntyre, IEEE Trans. Nucl. Sci. NS-53 (2) (2006) 620.

[4] W. Hennig, Y.X. Chu, A. Fallu-Labruyere, W. K. Warburton, R. Grzywacz, Nucl. Instr. and Meth. B, in press, doi:10.1016/j.nimb.2007.04.079.