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TECHNICAL DESIGN NOTE

Advances on detectors for low-angle scattering of epithermal neutrons

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Abstract
The Very Low Angle Detector (VLAD) installed at the ISIS spallation neutron source is a novel instrument for epithermal neutron scattering with a range of applications in solid state physics. VLAD extends the kinematical space of the VESUVIO spectrometer to low momentum transfers at neutron energies above 1 eV. Measurements at scattering angles as low as 1° have been made with limitations due to the achievable signal/background ratio.

Keywords: neutron scattering, resonant detector, high-energy inelastic neutron scattering

1. Introduction

The ISIS spallation neutron source of the Rutherford Appleton Laboratory can provide a large flux of neutrons in the epithermal range (1 eV $< E_n <$ 100 eV) and thus allows for scattering experiments with high energy exchange. Deep inelastic neutron scattering (DINS) [1] allows for energy exchange ω above 1 eV in the wave-vector range 20 Å^{-1} $< q <$ 250 Å^{-1}. The provision of an instrument able to reach momentum transfers as low as $q <$ 20 Å^{-1} while maintaining the same high energy transfer of DINS would allow for experimental studies in areas such as the dispersion relations of high energy excitations in metals and compounds [2], molecular electronic excitations and electronic levels in semiconductors [3] and magnetic materials [4]. The $q <$ 20 Å^{-1}, $\omega >$ 1 eV kinematical region, that we call high-energy inelastic neutron scattering (HINS) is now accessible thanks to the new Very Low Angle Detector (VLAD) bank of the VESUVIO spectrometer installed at ISIS. The main features of the new instrument are presented in this paper.

2. VLAD

VESUVIO [5] is an inverted geometry neutron spectrometer where the final neutron energy is measured in order to reconstruct the full scattering event kinematics. The combined HINS requirements of high energy transfers and low wave vector are achieved on VESUVIO through the use of high incident neutron energies (above 5 eV) together with small scattering angles. This translates into the need for detecting neutrons of tens of eV at scattering angles between 1° and 5°. Accordingly, the spectrometer has been modified by narrowing the neutron beam collimation and by fitting a new vacuum vessel, providing minimum attenuation of the neutrons scattered at low angles [6]. These are detected in the VLAD detector bank which is based on the resonant detector (RD) technique [7]. In the RD resonant radiative neutron capture in an analyser foil is used for energy analysis of the neutrons. The resonant foil (in VLAD a 25 μm uranium foil) strongly absorbs the neutrons over one or more narrow energy intervals; the absorption is followed by prompt gamma emission [8]. The detection of the photon cascade following neutron capture is done with yttrium aluminium perovskite (YAP) scintillators coupled to photo multiplier tubes and provides the arrival time of the neutron. Neutron energy spectra can thus be reconstructed with the time of flight technique.

The VLAD detector bank is shown schematically in figure 1 and a detailed description of the technical aspects of the detector mechanics is given in [6]. A total of 20 detector units, divided into five rings for optimal light collection and spatial resolution, cover the angular range 1°–3° at a distance

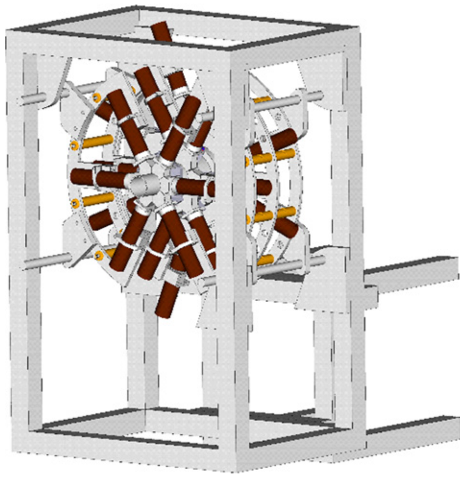

Figure 1. CAD drawing of the VLAD detector, showing the PM tubes and their supports around the neutron beam pipe. Neutrons come from the right.

of about 2 m from the scattering sample. Each detector unit consists of a trapezoidal uranium foil and a 6 mm thick YAP crystal of the same cross section. The scintillation light is collected via reflective light guides into 38 mm diameter PM tubes. The PM tubes are distributed radially around the beam axis. The position of the uranium foils determines the neutron scattering angle.

The need to pack a number of detector units into a small volume poses some design issues. Two effects have been the object of detailed analysis: cross-talk between adjacent detectors and neutron scattering effects inside the detectors. Cross-talk occurs when a photon, generated near a detector i, induces a recorded event in another scintillator j, coming either directly from the resonant foil i or from another crystal, for instance after Compton scattering. The cross-talk level κ_{ij} is here defined as the ratio between the events recorded in detector j and in detector i, when all the photons are originated in detector i. Unlike ambient background, cross-talk events have the same time pattern of 'good' (signal) events; consequently, they are indistinguishable from signal events in the TOF spectrum. Cross-talk events have been simulated with the GEANT4 code [12].

The κ_{ij} values for the VLAD bank are shown in tables 1 and 2 for two selected gamma-ray energies representative of ^{238}U emission lines. We observe that the κ_{ij} values are below 6% for both gamma-ray energies and they are significant mainly in the case of 'nearest neighbour' rings. This cross-talk level is acceptable since it represents only a small loss of angular resolution in the measurement.

Multiple neutron scattering inside the detectors was also investigated with GEANT4. All detector bank components (i.e. crystals, PM tubes, mechanical frame etc) are struck by the scattered neutron beam. This can cause neutrons of energy E_1 higher than the resonance value E_r to be detected after having degraded their energy to a level close to E_r through scattering in such elements. This provides a distortion of the detector response in the form of a tail of events at short flight times in the TOF spectrum. GEANT4 simulations were reported in

Table 1. Cross-talk matrix for five VLAD detector rings and a gamma-ray energy $E_\gamma = 1$ MeV. All values are expressed in %.

from to	1	2	3	4	5
1		3.2	2.2	1.2	0.7
2	3.5		3.3	3.0	1.5
3	2.0	1.8		2.8	2.4
4	1.0	1.4	1.7		4.7
5	0.9	1.0	2.1	5.1	

Table 2. Same as table 1 but for $E_\gamma = 4.06$ MeV.

from to	1	2	3	4	5
1		3.4	2.4	1.4	0.9
2	3.5		3.6	3.2	1.3
3	2.4	2.3		3.2	2.1
4	1.2	1.7	2.2		5.4
5	1.0	1.1	2.4	5.6	

Table 3. Some geometrical parameters of the VLAD detector bank.

Detectors	L_1 (cm)	2θ (deg)	Area (mm^2)
Ring 1	218	0.96	3276
Ring 2	206	1.53	2310
Ring 3	200	2.08	2982
Ring 4	199	2.63	3584
Ring 5	192	3.34	8600

[13] and show that such events do not give rise to significant artefacts in the TOF spectrum. Indeed the multiple scattering tail is negligible compared to other background components in VESUVIO (see below).

Table 3 summarizes the geometrical parameters of VLAD. The VLAD detector is set to be used with the standard ISIS data acquisition which features a time binning of the TOF spectra usually set to 0.25 μs.

3. Signal and background issues

The VLAD detector units are sensitive to the gamma background in the VESUVIO experimental hall. This can be seen in figure 2, which shows three TOF spectra recorded with the outermost VLAD detector ring (Ring # 5). The first spectrum (A) was obtained using a 2 mm vanadium slab as scattering sample. Clearly visible are two of the peaks due to resonant absorption in the analyser foils of elastically scattered neutrons of final energies $E_n = 6.67$ eV and $E_n = 20.86$ eV. The two peaks are riding on top of a continuous background. This background is rather large. In terms of the background intensity within a width of 3σ of the signal peaks, the signal/background (S/B) ratio is roughly 6% and 14% for the peaks at 220 μs and 360 μs, respectively. Similar S/B values are observed for the other VLAD rings. This large background level is the main limitation to the VLAD detector performance. We have therefore investigated the contributions to background. Most of the background must be due to gamma radiation delivering scintillation pulses of

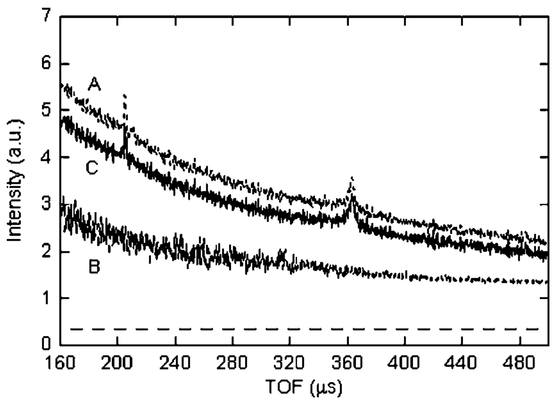

Figure 2. TOF spectra recorded by VLAD Ring # 5. A = reference V sample (recording time ≈10 h), B = no sample run (recording time ≈2 h), C = same sample as A but with the lead shielding described in the text (recording time ≈8 h). All the TOF spectra are normalized to the integrated proton current. The horizontal dashed line is the baseline level due to the ^{238}U radioactivity. The (signal) peaks in the full spectrum correspond to the ^{238}U resonances at 6.67 and 20.87 eV.

equivalent energy above 600 keV (which is the lower energy threshold of the discriminator electronics). A relatively small contribution is due to the natural radiation of the uranium foil. This background level is shown as a horizontal dashed line in figure 2; it was determined by fitting the TOF spectra at very long flight times ($t > 10^4$ μs). The remaining background originates from a number of sources. The spectrum labelled B in figure 2 refers to a measurement without a scattering sample in the beam (the poor statistics is due to shorter acquisition time of about 2 h instead of about 10 h in A). As discussed in [14], its origin must be associated with the target and moderator gamma-ray flash. This is largest at low t and decreases with a quite complicated shape, but that in the region of interest (up to about 400 μs) can be roughly regarded as an exponential with decay time of about 200 μs. Comparing plots A and B we can see that the effect of the sample is to enhance the background by about a factor 2 under the uranium resonances. In order to reduce the gamma background from target and moderator, different collimation-shielding devices have been tested. The best device is made of a high-purity lead shield with a hole of about 35 mm diameter, positioned just before the final beam collimation elements. In plot C of figure 2 we can see the effect of such a shielding in reducing the background. The improvement of the S/B ratio is about 1.15 and 1.3 for the two ^{238}U resonances at 6.67 eV and 20.86 eV, respectively. The improvement in S/B ratio, although modest, provides an indication for further detector performance improvements. Use of antimony-free lead alloys is essential in order to avoid the contamination by spurious peaks of the TOF spectra due to resonant neutron absorption in antimony.

A further method to enhance the S/B ratio was studied, in the form of using 'sandwich' detectors units, made of two scintillator crystals placed on either face of a uranium foil and a coincidence set-up. Preliminary tests [15] have shown encouraging results, with a five-fold improvement in the S/B ratio. However, in the coincidence configuration the signal intensity is at least one order of magnitude smaller than for the individual detectors. These tests show that a coincidence measurement with VLAD RD units would only be practical under measurement conditions where the signal intensity is large, which is usually not the case on VESUVIO. For this reason, the coincidence method, although the most valid in general for the RD configuration, has not been chosen for the definitive VLAD detector array. Plans for the reduction of the S/B ratio are now devoted to: (1) an improved lead shielding and (2) the design of a neutron absorbing coating for the sample tank in order to reduce the number of multiply scattered neutrons in the VESUVIO block-house. The latter device should be made of a Li^6 enriched material: in fact, the neutron capture reaction in lithium does not produce gamma-rays, that could be a further source of background in the RD detectors. Simulations are currently underway with GEANT4 with a lithium-enriched resin and will be the subject of future publications. The aim of the simulations is to optimize the shielding for a two-fold reduction of the neutron-induced background.

4. Conclusions

We have presented the advances in the design and realisation of the Very Low Angle Detector bank for high-energy inelastic neutron scattering at the VESUVIO spectrometer at ISIS. Use of simulations for the detector characterization has been presented. Measurements at scattering angles as low as 1° have been made with limitations due to the achievable signal/background ratio.

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