Condensed matter studies with 20-100 eV neutrons: effective detection systems for high inelastic neutron scattering and deep inelastic neutron scattering

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Strong demand exists for detection systems for neutrons of high energy coupled to low wave-vector transfer, facilitating new experimental investigations in condensed matter systems. Recent studies using the VESUVIO detector demonstrate a feasible and effective technique.

The provision of a high energy inelastic neutron scattering (HINS) regime on the VESUVIO detector would allow experimental studies in areas such as the dispersion relations of high energy excitations in metals, semiconductors and insulators, high-lying molecular rotational-vibrational states, molecular electronic excitations and the electronic level in solids. Such a facility would provide access to the unexplored kinematical regions of (q, hw) space (i.e. q < 10 Å⁻¹, 300 meV < hw < 5 eV) and would complement the current deep inelastic neutron scattering (DINS) regime where, with hw > 1 eV coupled to a wave-vector range 20 Å⁻¹ < q < 250 Å⁻¹, it is possible to probe the short time single particle dynamics (the momentum distribution n(p)) and the mean kinetic energy, \langle E_p \rangle in quantum and molecular systems.

It is well known that the combined requirements of high hw and low q are achieved in neutron spectroscopy through the use of very high incident energies coupled with very small scattering angles. Indeed, in the current resonance foil spectrometer (RFS) configuration, \(^{6}\text{Li}\) scintillators record only up to about a neutron final energy of 20 eV. In recent years a different detection concept has been thoroughly investigated, namely the resonance detector spectrometer (RDS). The RDS principles are indicated in figure 1 and compared with RFS; the configuration exploits resonance radiative neutron capture for energy analysis.

The RDS configuration was first tested on the eVS spectrometer using a Na(Tl) scintillator coupled to a \(^{238}\text{U}\) analyser foil. The Pb recoil spectrum was recorded up to a final neutron energy of 66 eV and the data proved comparable to those measured in the standard RFS configuration.

A further experiment included two novel detector materials, namely cadmium zinc telluride (CZT), a semiconductor detector, and a cerium-doped yttrium aluminium perovskite (YAP) scintillator. Both the solid state detector and the scintillator were tested on VESUVIO for DINS measurements on Pb and H₂O.

The main advantages of CZT detectors over other semiconductor types are their high atomic number and high bandgap value. CZTs have been used without any shielding in the neutron environment and performed very well at room temperature. An example of a typical time of flight (TOF) spectrum from a Pb sample recorded with a single, 0.25 cm² area, CZT detector is shown in figure 2. Two distinct regions can be clearly identified: one at t < 1000 μs, showing four free recoil peaks of Pb corresponding to final neutron energies equal to the high resonances for the \(^{238}\text{U}\) foil; the other at t > 1000 μs where the CZT directly records thermal neutrons diffracted from Pb lattice planes. The latter, due to the large thermal neutron absorption cadmium cross section, are a unique feature of this detector: measurements of epithermal neutron scattering (DINS) in the energy range 10 eV-100 eV can, through the use of an
analyser foil, be performed with simultaneous thermal neutron diffraction via direct detection in the Cd present in the detector itself.

A biparametric acquisition system has also been set up to perform simultaneous measurements of TOF and pulse height (energy) spectra. It allowed the investigation of both the γ emission corresponding to each observable neutron resonance and the TOF spectra selected in any desired γ energy interval. Results have included finding that the resonance γ emission, in terms of γ line relative intensities, is mostly independent of neutron energy and that at higher photon energies (above 180 keV), an increasing difference in intensity between on-resonance and off-resonance spectra can be found. A key result of RDS is therefore that in the explored energy range, there is no appreciable energy dependence of the detection efficiency as compared to RFS. In addition, an enhanced signal to background ratio (S/B) is envisaged at higher photon energies.

The latter feature has been investigated performing a series of other measurements on VESUVIO using a YAP scintillation detector. YAP is a fast, mechanically strong and chemically resistant scintillation material which has also been used in the neutron and γ environment with no shielding. Biparametric data acquisition also allowed the study of the R value as a function of the lower level discrimination (LLD) threshold. An optimum LLD was found at about 600 keV in order to prevent recording of the strong 108B-induced γ background emission at about 478 keV. The improvement in R value can be appreciated in figure 3, where the TOF spectra recorded by YAP during DINS measurements on a Pb sample are shown for two different LLD settings. The advantage of the RDS is twofold. Firstly, the experimental signal is obtained as a direct measurement rather than by a difference between foil in and foil out spectra as in the RFS. Secondly, γ detectors are ideally suited for revealing high energy neutrons because they do not suffer from the poor efficiency and excessive background rates of 6Li scintillators.

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Fig. 2: TOF spectrum collected with a CZT detector, placed at 2θ = 38° in the time interval 50 μs – 20000 μs. A blow-up of the thermal region (2000 μs – 20000 μs) shows the diffraction pattern from Pb (top right).

Fig. 3: TOF spectra recorded by a YAP scintillator (at 2θ = 25° and L2 = 1 m) in DINS measurements on a Pb sample with two different values of the LLD: (a) 40 keV, and (b) 600 keV. On average, the peak to background improvement by raising the LLD from 40 keV to 600 keV is a factor of about 10.