TRIPLE AXIS SPECTROMETERS

K.N. CLAUSEN
Risø National Laboratory,
Roskilde, Denmark

Abstract

Conventional triple-axis neutron spectroscopy was developed by Brockhouse over thirty years ago[1] and remains today a versatile and powerful tool for probing the dynamics of condensed matter. The original design of the triple axis spectrometer is technically simple and probes momentum and energy space on a point-by-point basis. This ability to systematically probe the scattering function in a way which only requires a few angles to be moved under computer control and where the observed data in general can be analysed using a pencil and graph paper or a simple fitting routine, has been essential for the success of the method.
These constraints were quite reasonable at the time the technique was developed. Advances in computer based data acquisition, neutron beam optics, and position sensitive area detectors have been gradually implemented on many triple axis spectrometer spectrometers, but the full potential of this has not been fully exploited yet. Further improvement in terms of efficiency (beyond point by point inspection) and increased sensitivity (use of focusing optics whenever the problem allows it) could easily be up to a factor of 10-20 over present instruments for many problems at a cost which is negligible compared to that of increasing the flux of the source. The real cost will be in complexity - finding the optimal set-up for a given scan and interpreting the data as the they are taken. On-line transformation of the data for an appropriate display in **Q**, ω space and analysis tools will be equally important for this task, and the success of these new ideas will crucially depend on how well we solve these problems.

Introduction

Over the years many individual components have been modified leading to improvements in intensity, resolution, signal/noise, automation, and analysis. Cold, thermal and hot moderators have been installed at many reactors and triple axis spectrometers have been specialised in the same three varieties - each type optimised for its corresponding spectrum.
The development of neutron guides has allowed cold high resolution triple axis work to move into the less confined spatial surroundings and the lower background of a neutron guide hall.
The crystals used to produce the monochromatic beam have improved dramatically. Pyrolytic graphite with its high reflectivity[2] provided the first major leap forward. Heusler alloy crystals has opened the field of polarised neutron scattering[3], which allows separation of nuclear and magnetic scattering, and a direct determination of the symmetry of magnetic excitations, the penalty however is a large intensity reduction.
The use of vertically and horizontally focusing monochromators and analysers allows significant increases in intensity at the expense of **Q** resolution[4,5]. At a selection of discrete wavelength or wavelength bands higher order spurious scattering processes can be largely eliminated through the use of filters such as polycrystalline Be, BeO or poor mosaic pyrolytic graphite[6,7]. The lack of tuneable filters does however constrain

the usable neutron energies, which may dictate an unfavourable intensity-resolution optimisation.

The neutron spin echo method proposed by Mezei[8] has been developed into a miniaturised version by Zeyen[9] using optimally designed field coils. This design can be implemented on triple axis spectrometers yielding an improvement in relative energy resolution of three orders of magnitude.

Large sample tables and a steady progress in the range of sample environments available for neutron experiments is another significant factor for the success of the triple axis spectrometer.

The advances in computing have yielded instruments that are both more flexible and easier to use i.e. it is possible to control both the instrument with focusing devises plus the sample environment and finally display the results including a first simple on-line display and analysis of the data.

The effect of monochromators, collimators and neutron optical elements on the resolution of the spectrometer and hence the expected intensity and peak shape is central to both the use and design of modern triple axis spectrometers. The first approaches were very useful for the understanding of kinematical focusing[10] and for a detailed peak-shape analysis[11] of a spectrometer without focusing elements. A more general description uses a matrix formalism, and treats the different optical elements of a spectrometer as a series of phase space transformations. The latter description can be studied in a paper by Popovici and Yelon[12] and the references therein. Software enabling the use of these methods on-line during the experiment is available on most instrument computers.

Several unsuccessful attempts to bring the triple axis spectrometer beyond point by point inspection has been made by Brockhouse[13], Dolling[14,15] and Kjems[16]. There are several different reasons for the lack of success for these instruments. They were too complicated to operate, they were either too constrained in there settings due to bulky shielding around the different analyser systems or had too high a background because of a very open geometry. The improvement beyond point by point inspection is only practically useful if it allows several points covering a few resolution width to be recorded at the same time, i.e. to measure a complete or a large part of a standard scan with only one setting of the spectrometer. The RITA instrument[17], which is being implemented at Risø now, is an attempt to exploit the throughput of an area detector together with optimised beam optics to increase the efficiency of a crystal monochromator-analyser spectrometer. This instrument is based on the lessons from the previous attempts. It is re-designed all the way from the cold source and outwards i.e. it is not just an add-on to an existing spectrometer, and furthermore it is believed that the actual hardware just is a start. Without the right software it will be used as a standard triple axis spectrometer (which is one limit of operation). The challenge is writing the software required for a simple user-friendly interface, which will be able to fully exploit the RITA capabilities. This will require efforts similar to the design efforts that has gone into the hardware.

The main emphasis in this paper has been be on triple axis spectrometers at a continuos source, but some of the ideas described may also be relevant for an indirect geometry inelastic scattering instrument similar to PRISMA[18], which might be implemented at a spallation source.

This paper was presented at an IAEA consultants meeting 16-19 March 1996 at Bhabha Atomic Research Centre, Bombay, India on the *Trends and Techniques in Neutron Beam Research for Medium and Low Flux Research Reactors.* It is therefore

not intended to be complete, but references have whenever possible been selected to complement each other and cover different important aspects of triple axis spectrometer design. The remaining part of the paper will be devoted to short discussions of the different components necessary for a triple axis set-up, with useful references for further reading.

Designing triple axis spectrometers

In most instances the task of designing a new spectrometer is severely constrained by the beam port, the space allocated to the spectrometer and the budget, i.e. the technical solutions chosen will be the result of a complicated set of compromises. For triple axis spectrometers especially it is important to bear in mind that ultimately it is the signal to noise ratio which determines whether an experiment is doable or not. i.e. even though shielding and shielding considerations are much less appealing to the designer, it is extremely important not to neglect this. This will in the future become even more important. For the most effective use of neutrons, the detector system will have to be rather open (area detectors) and the use of collimators should be avoided if an open geometry with clever optics can provide the required resolution with higher intensity in a different way.

Flexibility and modularity

A triple axis spectrometer is not an instrument that once build will stay in that same form forever. It will develop as new problems needs to be examined, new ancillary equipment, better optical elements or improved control software becomes available. The spectrometer components, control system and the system for visualisation and analysis of data should all be modular. With a flexible modular spectrometer design, improved performance can often been obtained at relatively low cost in term of components or equipment. The most essential ingredient is commitment, human resources and talents.

Cold, thermal and hot sources

The most useful moderators for triple axis spectrometers are cold and thermal sources. In heavy water moderated reactors the thermal source can either be a small container with D_2O placed as close to the core as possible in a beam tube passing tangential to the core, or direct view of the D_2O moderator. In H_2O cooled and moderated reactors a D_2O tank or a Beryllium reflector around the core is the ideal position for the sources. The temperature of the moderator in research reactors is normally around 320 - 350 K, and the corresponding spectrum will approximately follow a Maxwell-Bolzmann (MB) distribution with this characteristic temperature. (See fig. 1). A compilation of different cold source designs can be found in the proceedings from an *International Workshop on Cold Neutron Sources* held at Los Alamos, USA in 1990[19]. Three different designs of cold sources all operating at 20 - 35 K have demonstrated the best characteristics: boiling D_2, boiling H_2 or supercritical H_2 . If the cold source has not been designed into the system from the start, the choice of system is often dictated by geometrical constraints in the reactor or the beam tube. Deuterium has a lower scattering cross section and lower absorption than hydrogen. i.e. a

deuterium source is generally larger (5 - 25 litres) and can be used with a re-entrant hole, in which the beam tube ends. The beam thus only sees the centre of the source and the corresponding spectrum is close to a true MB distribution (see fig. 1). The supercritical hydrogen system is a single phase system (operating at 15 bar), and its main advantage is the freedom to arrange the feed lines from the cryo-cooler to the source which can be required for horizontal installation in a small beam-tube. In the hydrogen sources (from 1 to a few litres of hydrogen) a larger proportion of the scattered neutrons escapes from the outer layers of the source without being fully thermalised, i.e. the distribution is MB with a tail towards thermal neutrons. Solid D_2O ice or methane cold sources should be avoided. From an intuitive licensing point of view these sources might sound more interesting, but in reality the hydrogen sources are better, safer and more reliable.

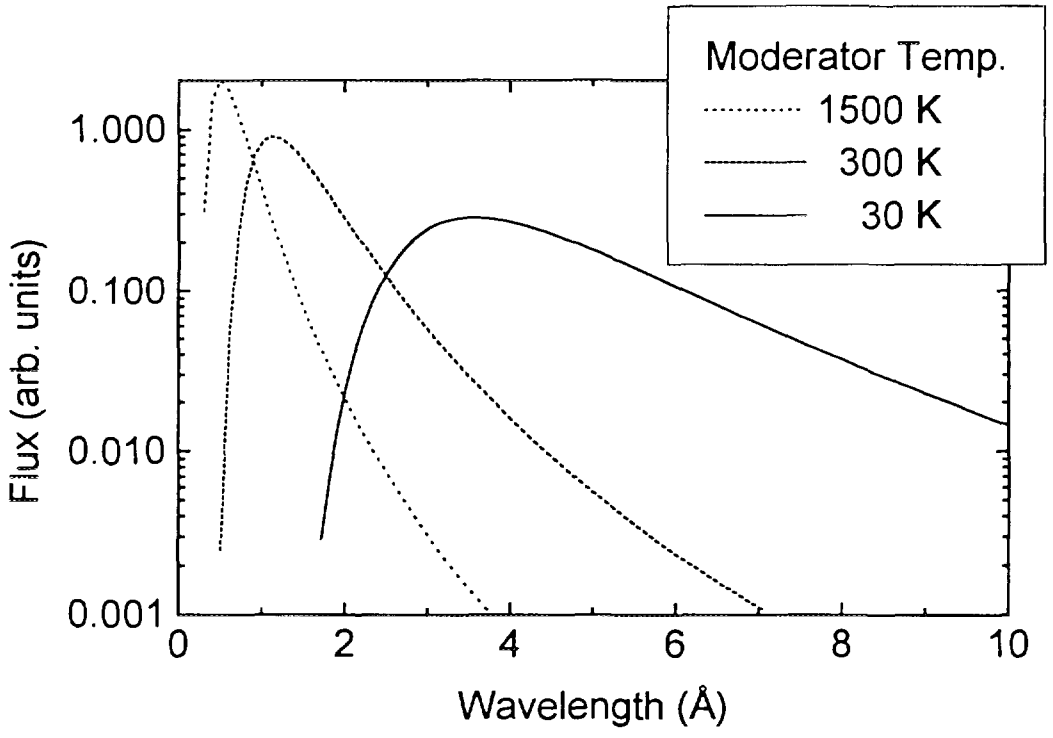

Fig 1. *Maxwell-Bolzmann distributions functions for temperatures corresponding to the operating temperatures of cold, thermal and hot moderators.*

A hot source is basically just a piece of graphite, which is heated to 900 - 1200 K by γ radiation from the core of the reactor. The use of crystal spectrometers for hot neutrons is however non-trivial. Hot neutrons are very penetrating and it is often difficult to make sufficiently effective shielding. The results are furthermore hampered by a multitude of possible spurious peaks. If not carefully shielded the installation of a hot source in an existing reactor could jeopardise the background of neighbouring instruments. It is my personal opinion that high energy inelastic scattering should be performed at pulsed sources. Hot to epithermal neutrons constitutes by virtue of the functioning of a spallation source a large proportion of the energy spectrum (high intensity), spurious effects are avoided by means of the time structure, and the source

is effectively switched off when the scattered neutrons are being detected (low background).

From the reactor to the monochromator - cleaning the beam

One of the most effective means to reduce the background on the spectrometer is to stop unwanted radiation as close to the source as possible. Fast neutron contamination can be strongly reduced by single crystal filters just after the source. The most commonly used such filters are sapphire, bismuth, quartz, silicon, beryllium or graphite. In figure 2 the neutron transmission of 2 different 10 cm single crystal sapphire filters attenuating fast neutrons is shown[20,21]. For very good quality crystals the fast neutron contribution can be reduced by more than a factor of ten with a transmission of the wanted neutrons of the order of 80% or more.

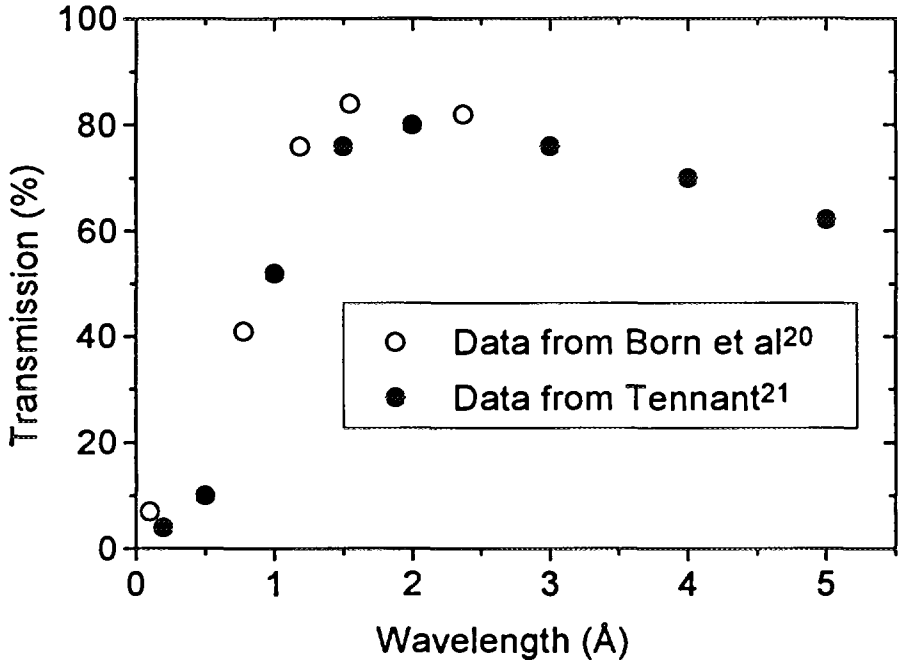

Fig. 2. *Neutron transmission of 10 cm thick sapphire filters at room temperature.*[20,21]

Sapphire crystal filters have proven to be the best, but also most expensive filter for cold and thermal spectrometers[20,21]. For cold neutrons a coarse low cost mechanical velocity selector filter can be used[22,14] as a combined higher order filter and band-pass filter for the suppression of background from unwanted neutrons around the monochromator, Such a filter is tuneable, allows a large divergence to pass (1° - 2°) with a transmission in excess of 80% and a transmission of higher order neutrons of the order of 10^{-4}.

With a supermirror channel in the outer parts of the beam channel from the monochromator, a larger divergence can be transmitted and the background reduced because the window for the beam can be reduced in dimensions. A combination of these methods have reduced the fast neutron content on the monochromator position on RITA at Risø by a factor of 4 and increased the cold to thermal neutron flux by a factor between 2 and 3.

Supermirrors

Supermirrors are periodic layered structures, which has an effective critical angle m times larger than standard Ni. The enhancement is due to Bragg reflection from a multilayer structure. The reflectivity is in excess of 99% up to the critical angle for Ni ($Q_c \approx 0.02$ Å^{-1} or $\theta_c \approx$ 6'/Å). The reflectivity curve for a m=4 supermirror produced by Peter Böni at PSI[23] is shown in fig. 3. Supermirrors with a large number of bilayers are excellent for short guides with only one to a few reflections. For long guides a reflectivity in excess of 99% is required and so far only Ni coating or supermirror with small m has been used.

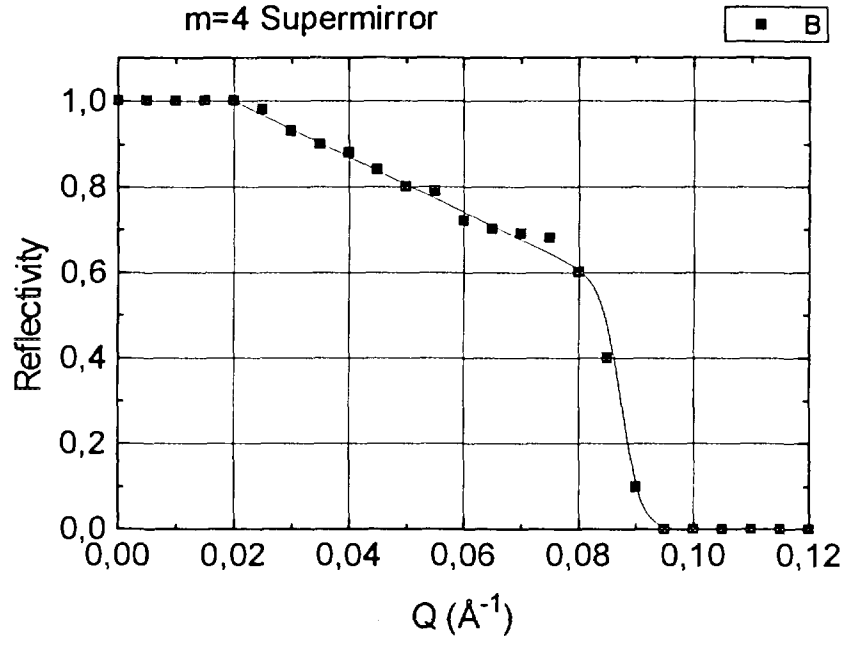

Fig. 3 *Measured reflectivity of a m=4 supermirror guide prepared at the Paul Scherrer Institute*[23]. *The line is a guide to the eye.*

For cold neutrons tapered supermirror beam-channels or even better supermirror beam-channels which approximates to a parabolic shape can be use for real space focusing. Magnetised supermirrors can also be used as excellent beam polarisers.

Shielding materials

A compact design is often a wish for intensity reasons, but is in many cases a must, because of limited space available for the spectrometer. In this case it is especially important to use Monte Carlo code to simulate the actual radiation emerging through the beam tube from the reactor and the radiation scattered in the monochromator and its surroundings. Using this approach the optimum composition can be calculated for 1) the beam stop, 2) material which can be in the direction of the scattered beam from the monochromator and 3) more general purpose shielding material used in the monochromator drum. With the conditions relevant to the spectrometers at Risø, the optimal composition for the general purpose material[24] could be composed of a lead, boron and hydrogen mixture with a density of 4.6 g/cm^3, 1 atom % of natural boron

and as much H as possible. We have produced this new composite material by extruding 12 mm balls consisting of approximately 50% Pb pellets and 50% polyethylene, and casting these balls in a mixture of H_2BO_3 and polyester. The composite material is substantially better than the old heavy concrete solution. The other materials in the monochromator drum has been selected in a similar way.

Monochromator/analyser crystals

The performance of a triple axis spectrometer depends crucially on the properties of the monochromator and analyser crystals. The reflected wavelength is determined by Bragg diffraction i.e.

$$\lambda = 2d\sin(\theta)$$

where d is the interplanar distance and θ is the Bragg angle. The wavelength band-width selected by perfect crystals are too narrow for most practical applications, unless they are used in open geometry's and elastically bent i.e. used as a focusing monochromator[25]. The intensity can be increased substantially by selecting a bandwidth whose contribution to the overall resolution of the spectrometer is matched to the corresponding angular divergence to the beam.
The selected band-width can be tailored by introducing defects in the crystals:

$$\frac{\Delta\lambda}{\lambda} = \cot(\theta)\Delta\theta + \frac{\Delta d}{d}$$

where $\Delta\theta$ and Δd represent uncertainties in the orientation of the lattice planes (mosaic crystals) and the lattice spacing (gradient crystals) respectively. For a thorough review of the status of monochromator materials see the articles by Magerl[26] ,Götz[27] and the *Proceedings of the Workshop on Focusing Bragg Optics*[5].
For resolutions in the meV range **mosaic crystals** are generally used. Beam divergences of the order of 0.5°, are matched to a mosaic width of the same value and results in a wavelength resolution of the order of 1%. The peak reflectivity for a perfect mosaic crystal is given by[27]

$$R_{id} = \sqrt{\frac{4\cdot\ln(2)}{\pi}}\frac{|F|^2\lambda^3 n^2}{\sin(2\theta)\sin(\theta)}\frac{t}{\eta}$$

n is the number density, F the structure factor, t the sample thickness and η the mosaic width. Secondary extinction leads to saturation effects, and the actual reflectivity is given as:

$$R = \frac{R_{id}}{1+R_{id}}$$

For wavelength above approximately 1.5 Å the best material is HOPG highly oriented pyrolytic graphite. The mosaic width is normally in the range 0.5 to 1 degree. Below 1.5 Å several candidates are used, plastically deformed Cu are produced rather standard for instance at the ILL. The main draw-back with Cu is the activation in a neutron beam, which makes Cu difficult to handle after irradiation. Be is another good candidate, but the technique to get good mosaic crystals is still not fully developed. Composite Ge monochromators[28] are developing rapidly at present and will in many cases replace Cu (Ge will not be activated in the beam). The important parameters for monochromator materials are: a large number density and coherent scattering length, a high Debye temperature and low absorption and incoherent cross section plus last but not least technical solutions to produce large crystals with a homogenous mosaic distribution.

In the table below a list of useful parameters for typical monochromator materials are given:

Table 1 List of properties for selected monochromator materials, a, c are lattice parameters, n the number density, θ_D the Debye temperature, σ_c and σ_i are the coherent and incoherent scattering cross-sections and μ_{abs} the linear absorption length. F is the structure factor[27].

Material	lattice	a c [Å]	n [Å^{-3}]	θ_D [K]	σ_c [b]	σ_i [b]	μ_{abs} [cm^{-1}]	$\lvert F\rvert^2$ [b]
PG (002)	hexagonal layered	2.46 6.71	0.057	420	5.50	0.01	0.0005	0.44
Ge (hkl) all odd all even	Diamond	5.66	0.044	366	8.80	0.20	0.058	 0.35 0.70
Si (hkl) all odd all even	Diamond	5.43	0.050	658	2.16	0.04	0.04	 0.09 0.17
Be	hcp	2.29 3.58	0.12	1160	7.53	0.06	0.0005	0.60
Cu	fcc	3.61	0.085	339	7.8	0.7	0.19	0.62

Gradient crystals are used for very good energy resolution (μeV), where the set-up is almost in a backscattering configuration.
The most commonly used **polarising monochromator** is the Heusler-alloy, which is quite difficult to make and have relatively small reflectivities. A very promising new development is the ^{3}He filter polarisers[29]. It is a cell with polarised ^{3}He which only absorbs one spin state. This type of polariser is expected to be available within the next few years, and has the advantage that monochromatisation and polarisation are de-coupled, i.e. we can use the best possible monochromator and focusing system in front of the filter. For long wavelength neutrons, magnetised supermirrors can used to polarise the beam.

Focusing monochromator and analyser systems

The first focusing systems to be used were vertically focusing monochromators[30,5]. They allows the use of smaller samples by increasing the flux on the sample by a factor of two to five at the cost of a degraded resolution out of the scattering plane. In most cases this has no adverse effects on the interpretation of the results. A vertically focusing analyser reduces the background by focusing the scattered beam onto a smaller detector.

The merits of horizontal focusing systems are similar - smaller samples, reduced background. In the horizontal plane we normally want better resolution. In many cases this can still be obtained using focusing as a tool to shape the resolution function. One method is to make monochromatic focusing, which maintain good energy resolution and a reduction in background by allowing a narrow diaphragm at the focal point in the incident beam.

A doubly focusing monochromator or analyser is a complicated mechanical set-up[31], which combines the virtues of both horizontal and vertical focusing. A very powerful triple axis spectrometer using a doubly focusing monochromator and analyser and monochromatic focusing is installed at the ORPHEE reactor in Saclay and described in detail by Pintschovius[4].

Spin Echo type triple axis spectrometers

Neutron spin-echo spectrometers were until recently huge instruments, but the development of new coil systems by Zeyen[32], has miniaturised the set-up (small diameter coils), simplified the operation (the resolution is well behaved up to the maximum Fourier time), reduced the cost to about 10% of a complete triple axis spectrometer and allowed the use of large beam divergences (intensity gain). With this type of set-up a relative energy resolution of 10^{-5} has been obtained at the ISSP thermal triple axis spectrometer in Japan[33], i.e. a gain of three orders of magnitude over standard triple axis spectrometers. On the proposed superconducting version at the ILL a relative energy resolution of 10^{-6} is expected[9]. The only intensity penalty stems from the fact that polarised neutrons are used. At the ILL a new spectrometer TASSE (Triple Axis Spectrometer with Spin Echo) is being developed. With this instrument complete phonon focusing (matching both slope and curvature) should be possible for the study of excitation lifetimes[9]. Ultra-high resolution measurements using a spin-echo add on to a triple axis spectrometer is however best suited at a high flux reactor.

TAS with Elasticity bent perfect monochromator and analyser

Kulda[34] at the ILL has demonstrated that a triple axis spectrometer with elastically bent perfect Si (111) monochromator and analyser crystals can be a cheap alternative to and in some cases outperform a standard Soller collimated triple axis spectrometer with flat PG (002) monochromator and analyser crystals. With properly optimised vertical and horizontal focusing very efficient real space focusing can be obtained, and the Soller collimators necessary for a similar resolution on the PG (002) system can be omitted. The Silicon set-up has furthermore the advantage that second order contamination is eliminated. If larger samples are available, then a system with a mosaic monochromator and analyser are in general more flexible.

Multi-element analyser system

An attempt to get beyond point by point inspection is realised in the analyser set-up for RITA[17]. This paragraph is an update on the description in the paper by Mason[17]. The single analyser-detector pair of a conventional triple axis is replaced by an array of seven independently orientable, flat vertical vanes of pyrolytic graphite, which scatter neutrons onto a microstrip area detector. By rotating each blade independently, as well as the entire array, it will be possible to choose different modes of operation. A flat analyser, together with Soller slit collimators and an electronically selected window in the centre of the area detector is the standard triple axis geometry - and is one limit of operation. Removing the collimators one can employ the standard horizontal focusing geometry onto the centre of the detector (shown schematically in fig. 5a). In this case each analyser blade is set for the same energy, all of them focus on the same point on the detector, and the analyser array is set at an angle ψ_A with respect to the scattered beam:

$$\tan(\psi_A) = \frac{1}{\left(\frac{AD}{SA \cdot \sin(2\theta_A)} + \cot(2\theta_A)\right)}$$

SA is the sample to analyser distance, AD is the analyser to detector distance, and θ_A is the analyser Bragg angle for the desired neutron wavelength. (see fig. 4a). Here the integrated intensity in the spot in the centre of the detector is an integral in **Q** space at constant energy transfer, i.e. with individually adjustable vanes, monochromatic focusing can be obtained without having AD = AS. Tests of this analyser set-up - for both incoherent elastic scattering from vanadium and inelastic magnetic scattering - have shown a factor of five increase in intensity in point focusing mode when compared to a flat analyser. The vanadium energy width was slightly better than for the flat analyser.

The virtues of horizontally focusing analysers for measurements where **Q** resolution can be sacrificed but good energy resolution is required have been known for many years. RITA, because of its area detector, can also operate in line focusing mode (shown in fig. 4b) where the analyser blades are dispersed across the face of the detector. In this case a constant energy scan perpendicular to the $\mathbf{k}_f$ ($\mathbf{k}_f$ is the **k** vector of the outgoing beam) runs across the detector so that the gain in efficiency of horizontal point focusing is realised without the loss in **Q** resolution (the scan is actually an arc and not a line, but this is not a significant effect given the finite resolution).

The resolution of each analyser is determined by its mosaic spread and the effective distance collimation (1 degree for a point sample at 60 cm with a 1.5 cm wide analyser at 74 degrees $2\theta_A$). Because the angular separation of the analysers is the same as the collimation, each point is correctly spaced with respect to the size of a resolution element. With seven vanes an area detector, 15 cm wide, will accommodate the beam. Of course this gain is only useful if the background does not increase too much. i.e. the front end of the instrument must be carefully designed.

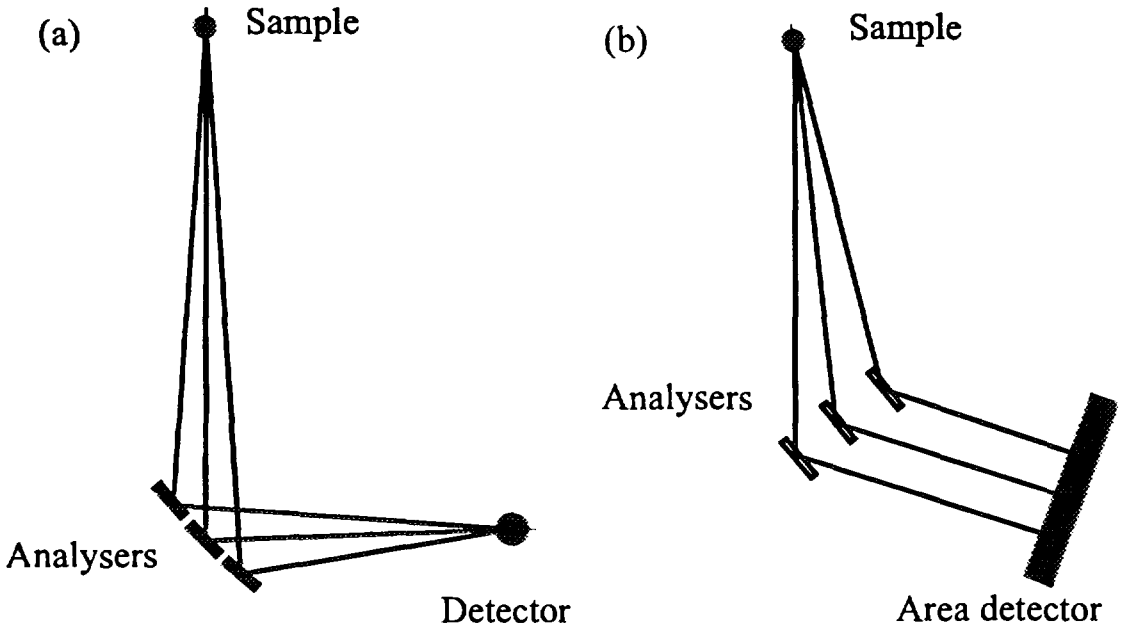

Fig. 4 *Schematic illustration of a multi-element analyser operating in a) point focus and b) line focus mode. For clarity only three blades are shown.*

In addition the analyser tank will be evacuated (with a sapphire window) to prevent neutrons from scattering off air and into the area detector which could otherwise be a problem when operating without Soller slit collimators (air scatters about 5 % per metre due to the incoherent cross section of nitrogen). Tests of the analyser tank have shown that the background per unit detector volume is lower than on the existing Risø triple axis machines which in part can be attributed to the lack of wedges in the design. Measuring at more than one **Q** and ω is only useful if it can be arranged so that the additional data is at interesting locations (this was part of the problem with the Chalk River multi-analyser system).

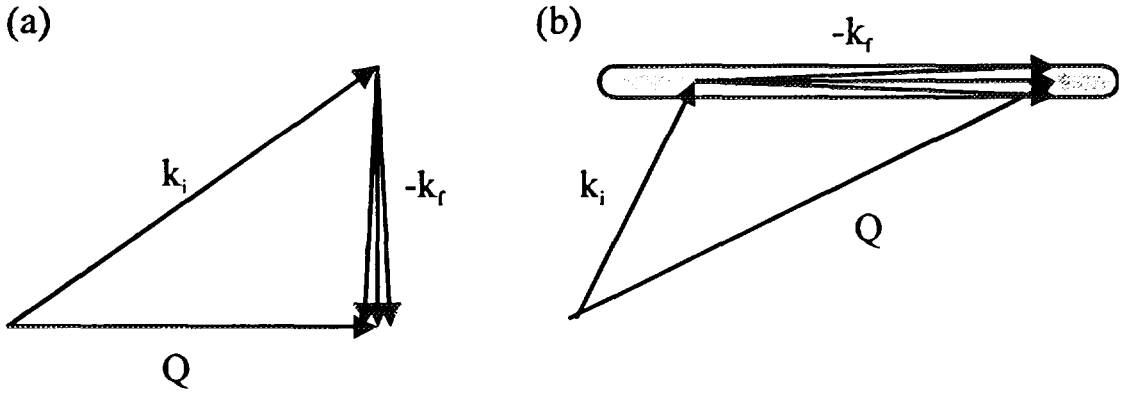

Fig. 5 *Scattering diagrams in reciprocal space for a constant energy focusing analyser showing a) orientation to produce a constant E scan aligned to approximately coincide with a high symmetry direction and b) a scan across a two dimensional rod of scattering in a two dimensional material. The array could be operating in point focus mode in which case an integral over the Q's shown would be measured or in line mode in which case the scan would be resolved across the detector face.*

In most condensed matter systems the scattering of interest is located in a small region of the four dimensional **Q**, ω space, the single resolution element spacing of the RITA analyser makes it ideally suited to a wide range of problems. By setting $\mathbf{k}_f$ perpendicular to a high symmetry direction in the crystal (as shown in fig. 5a) it is possible to perform a constant E scan in that direction.
The wavevector of the centre of the scan determines which $\mathbf{k}_f$ satisfies this condition, i.e a tuneable velocity selector higher order filter is needed in the incident beam. Figure 5b illustrates another situation, that of a two dimensional material where the scattering is independent of wavevector along a rod in reciprocal space. In this case the area detector scans at constant energy perpendicular to the rod and $\mathbf{k}_f$ can be selected based on resolution considerations alone since the degree of freedom needed to satisfy the scan condition is the displacement along the rod. Of course one can construct many different geometries subject to kinematic constraints, i.e. in general both **Q** and ω vary across the detector. A constant **Q** scan is however not possible in a single setting.
It is thus possible to focus a dispersive mode over the entire detector. Provided the scan is dispersed uniformly across the detector the intensity can be binned to optimise for intensity (summing the detector) or resolution (retaining the same number of bins as there are analysers) after the experiment is finished. Between these limits there is the possibility for a continuos trade off between intensity and resolution. The vertical detector elements can be treated in the same way although in that case only the component of **Q** perpendicular to the scattering plane is varying. As a cheap alternative the detector could be made from seven vertical ^{3}He tubes.

Control system and software

Today the cost of a control computer for a spectrometer is negligible compared to the cost of the rest of the system and advances in computer performance is so fast that the control computer should be a module in the system which can be easily changed, i.e. the hardware to control detectors, motors, ancillary equipment etc. should not be integrated as cards on the computer bus. A solution with a personal computer interfaced to the hardware by means of interfaces like VME, IEEE or RS232 is a flexible solution, which allows upgrades and replacements of the individual components without changing the whole system.
The more complex the system, the more essential will the software be. The experimentator should focus his attention on the features in **Q**, ω space he wants to study, and which resolution he requires. The setting of the spectrometer which most efficiently provide the answer, should then be suggested by the control system, and during the actual data taking the results should be optionally visualised either directly as the observed counts on the detector or in the appropriate cut in **Q**, ω space. The latter is a challenge and a task which is often underestimated, but which will be essential for the success of the investment.

Conclusion

The triple axis spectrometer is a versatile and powerful tool for probing the dynamics of single crystals. It has provided key information for our understanding of magnetism, superconductivity, phase-transitions, ion diffusion, lattice dynamics etc.

The excitations of crystals are in general either delta functions or narrow peaks centred around dispersion surfaces, i.e. information is concentrated in a limited fraction of **Q**, ω

space. Selectively focusing on a series of single points in this four-dimensional space has proven to be an efficient method, because each point has a large information content. Measurements based on a series of point by point scans are furthermore simple to control and easy to analyse. Hence the large success of the triple axis spectrometer. Improvement beyond point by point inspection on triple axis spectrometers will only be practically useful, if it allows several points approximately a resolution width apart to be recorded at the same time, i.e. to measure a complete or a part of a standard scan with one setting of the spectrometer. A multi-filament analyser and an area-sensitive detector, or a row of 7 to 10 single detectors is a suggestion for such an improvement. The same set-up would also allow a more efficient mapping of more extended regions in $\mathbf{Q}$, ω space from systems where the scattering function is a smoothly varying function of $\mathbf{Q}$ and ω, (e.g. powders, disordered systems, spin fluctuations in High temperature superconductors, broad quasielastic scattering etc.).

A triple axis spectrometer is also a versatile and flexible instrument which can be used in several different modes and for test of new instrumental concepts. In most small and medium flux reactors triple axis spectrometer are often also used as a diffractometer (for very weak scatterers where the background is critical), a diffuse scattering spectrometer (especially when fitted with an area detector), a reflectometer or to test reflectometer or SANS concepts. In general a triple axis spectrometer is also one of the best spectrometer types for training purposes.

A triple axis spectrometer should be build in a modular fashion, i.e. as a start a simple version could be build, and later the different axis, monochromator-analyser systems, guide optics or detector systems can be upgraded when improved components or funds are available. From the initial design it is however very important to carefully design the shielding for maximum efficiency, and choose an overall design, which is prepared for changes or upgrades.

The triple axis spectrometer is most powerful for cold and thermal neutrons. If a cold source is planned then hydrogen or deuterium moderated cold sources are to be preferred. Solid D_2O ice or methane should be avoided. From an intuitive licensing point of view the latter sources might sound more interesting, but in reality the hydrogen sources are safer, better and more reliable. A hot source for a crystal monochromator-analyser triple axis spectrometer at a low or medium flux reactor is less attractive.

On the triple axis spectrometer provisions should be made for the use of several methods for focusing optics. Monochromators focusing in the vertical plane is a minimum requirement. Provisions should be made for use of polarising filters i.e. magnetic materials should be avoided in and just around the beam channel. Ultra-high resolution measurements using a spin-echo add on to a triple axis spectrometer can not be recommended at a low or medium flux reactor. The possible flux will be to low to justify this extra investment.

Many new developments are pushing triple axis spectroscopy into new areas of parameter space and increased intensity and effectiveness is allowing smaller samples and weaker cross sections to be investigated. triple axis spectroscopy at steady state sources is an open an lively field where scientists with new ideas can make substantial

contributions, and triple axis spectrometers will continue to be the instrument of choice for many experiments, especially at good reliable reactors with cold sources.

One of the big challenges in the future will be how triple axis like experiments can be performed on new powerful spallation sources, and how some of the lessons and methods learned during the development of modern steady state instrumentation's can be used either directly or indirectly by stimulating improvements in instrumentation at spallation neutron sources, and vice versa.

Acknowledgements

During the whole RITA project I have had very frequent and long discussions with T. E. Mason, G. Aeppli, D. F. McMorrow, J. Søgård, B. Lebech and J. K. Kjems. Their support, contributions and advise has been absolutely essential for the project and cannot be over estimated. Stimulating discussions, advice and pre-prints from C. Broholm, P. Böni, G. Eckold, B. Hennion, J. Kulda, A. Schröder, U. Steigenberger, F. Tasset and C. M. E. Zeyen are gratefully acknowledged.

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