POLARIZED TRIPLE-AXIS SPECTROMETER TASP

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ABSTRACT

The polarized triple-axis spectrometer TASP at SINQ has been optimized for measuring magnetic cross sections in condensed matter. The neutrons are polarized or analyzed either by means of benders or Heusler monochromators. The beam divergence, i.e. the intensity, and the spectral range of the neutrons is rather large because of the supermirror coatings of the feeding neutron guide. The intensity can be further increased at the sample position by means of a focussing monochromator and a focussing anti-trumpet. The end position of TASP allows the tailoring of the neutron beam already before the monochromator and to scatter neutrons over very wide ranges of angles.

1. Introduction

The **T**riple **A**xis **S**pectrometer for **P**olarized neutrons, TASP, is a sister instrument of Drüchal [1]. Both spectrometers are built in an almost identical way. The main difference being that TASP is located further away from the cold source and has the option of using polarized neutrons. Therefore TASP will be particularly useful for the investigation of magnetic scattering and/or the differentiation between coherent und incoherent scattering contributions, for example in hydrogen containing materials.

The triple-axis spectrometer was invented almost 40 years ago by Brockhouse and the basic design has not changed since then. The first and the third axis, i.e. monochromator and analyzer, define the energy of the incident and the scattered neutrons, E_i and E_f, respectively, and the second axis defines the orientation of the reciprocal lattice of the sample with respect to the scattering vector $\mathbf{Q} = \mathbf{k_i} - \mathbf{k_f}$ (Fig. 1). The energy transfer from the neutron to the sample is given by $E = E_i - E_f$, where $E_\alpha = (\hbar k_\alpha)^2/2m_n$. m_n is the mass of the neutron. A so called constant-**Q** scan is performed by, for example, varying k_i, keeping k_f fixed, and by rotating the sample in such a way that **Q** remains constant with respect to the reciprocal lattice. The measured intensity $I(E)$ is then directly proportional to the scattering function $S(\mathbf{Q},\omega)$, i.e. the Fourier transform of the pair correlation function.

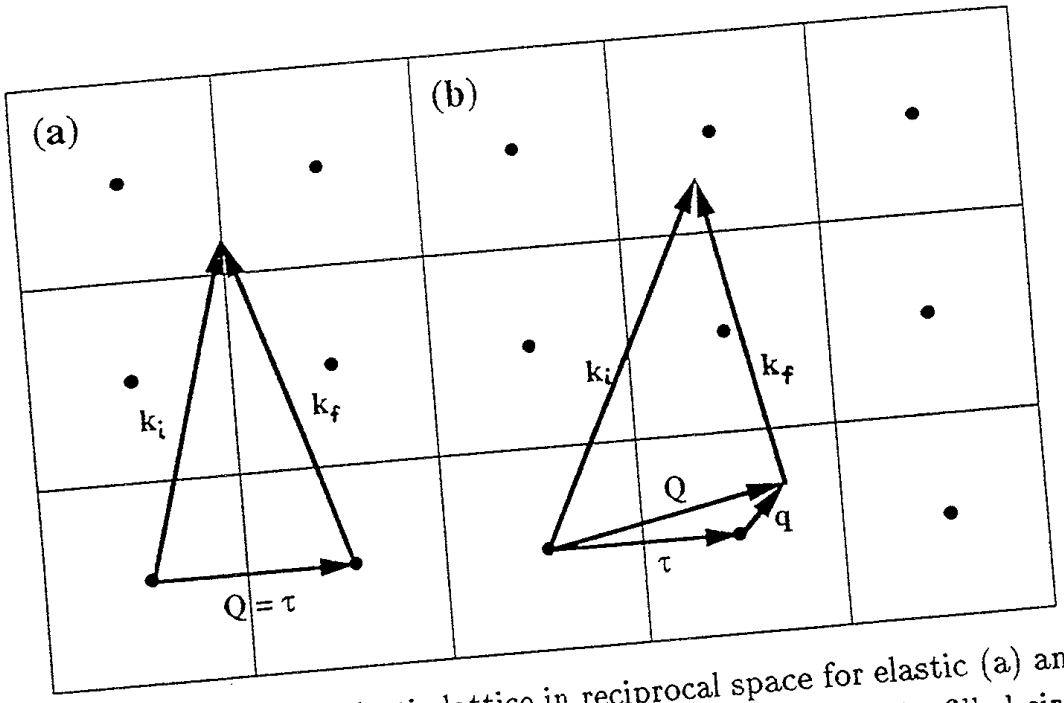

Fig. 1: Visualization of a quadratic lattice in reciprocal space for elastic (a) and inelastic (b) scattering. The lines indicate the Brillouin zone boundaries and the filled circles denote the zone centers.

In 1969, polarization analysis was introduced by Moon, Riste, and Koehler [2]. They polarized and analyzed the neutrons by means of appropriate, magnetized single crystals. Spin flippers before and after the sample were used to select the spin eigenstate of the neutrons (see Fig. 2). A measurement of the four different cross sections σ_{++}, σ_{-+}, σ_{+-}, and σ_{--} allows an almost unambiguous determination of the magnetic and nuclear scattering cross sections. For example, if $\mathbf{Q}$ is chosen to be parallel to the polarization of the neutrons, then all magnetic scattering is spin flip scattering (Table 1). Moreover, the difference intensity $|I_{\mathrm{HF}} - I_{\mathrm{VF}}|$ for spin flip (or non spin flip) scattering is purely magnetic, i.e. even nuclear spin incoherent scattering and (constant) room background scattering cancel.

Table 1: Magnetic, σ_{M}, nuclear (coherent), σ_{nuc}, and nuclear spin incoherent, σ_{NSI}, cross sections for the polarization analysis setup. σ_{BG} designates the background.

field	spin flip scattering $(-+)$ $(+-)$	non spin flip scattering $(++)$ $(--)$
horizontal: $\mathbf{B_h} \parallel \mathbf{Q}$	$\sigma_M + \frac{2}{3}\sigma_{NSI} + \sigma_{BG}$	$\sigma_{\mathrm{nuc}} + 0\sigma_M + \frac{1}{3}\sigma_{NSI} + \sigma_{BG}$
vertical: $\mathbf{B_v} \perp \mathbf{Q}$	$\frac{1}{2}\sigma_M + \frac{2}{3}\sigma_{NSI} + \sigma_{BG}$	$\sigma_{\mathrm{nuc}} + \frac{1}{2}\sigma_M + \frac{1}{3}\sigma_{NSI} + \sigma_{BG}$
difference intensity	$\frac{1}{2}\sigma_M$	$\frac{1}{2}\sigma_M$

Presently, most (cold) triple-axis spectrometers occupy intermediate positions at cold neutron guides, thus the angular range of the scattering angles at all three axis are often restricted in such a way that the so called "W" configuration cannot be used [3], thus yielding a resolution function that has a rather complicated orientation in the 4-dimensional momentum-energy space. Moreover, the intensity of incident neutrons with E_i larger than 20 meV is low because of the small divergence of the

Ni coatings of the (bent) guides. Therefore neutron energy loss spectroscopy is restricted to small energy transfers.

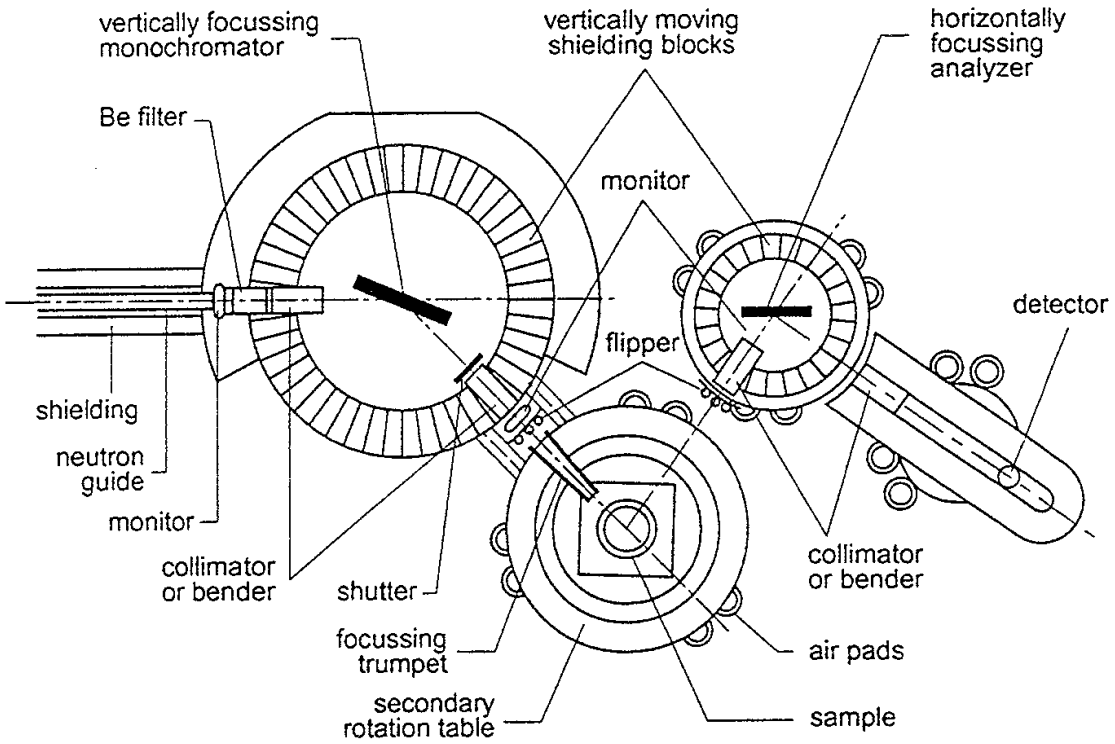

Fig. 2: Schematics of the polarized beam, triple-axis spectrometer TASP at SINQ. The instrument moves on air cushions.

Because all spectrometers at SINQ are fed by supermirror-coated neutron guides, the energy range of the incident neutrons is significantly enlarged (Fig. 3) [4]. In addition, the end position of TASP allows to insert filters and collimators before the monochromator and to use polarizing Heusler monochromators. Thus the dynamic range and the resolution conditions can be varied over a very wide range. In the following we describe some of the basic features of TASP. The technical specifications are given at the end of the paper. For details on the mechanical part see the contribution by W. Bührer [1].

2. Monochromator stage

The TASP monochromator stage occupies the end position of a 54 m long neutron guide that is fed by a D_2 cold source ($T = 28$ K). Due to the bending, γ and fast neutron background are significantly reduced. Moreover, the phase space and the polarization of the beam can be selected in the primary beam path without impeeding the performance of any other instrument (Fig. 2). The flux at the monochromator is increased by more than a factor of three for neutrons with a wavelength of $\lambda \simeq 4$ Å, because of the supermirror coating of the neutron guide (Fig. 3). The increase of the divergence of the neutron beam allows measurements with reasonable flux even at $E_i = 30$ meV.

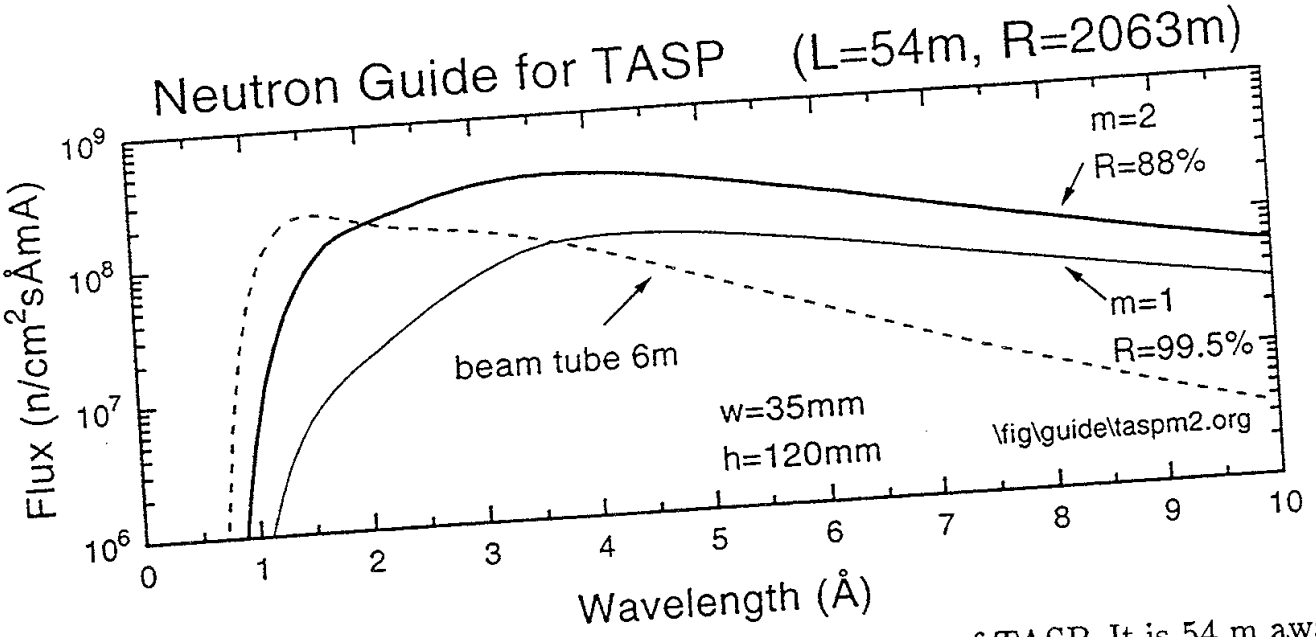

Fig. 3: Calculated neutron flux at the monochromator position of TASP. It is 54 m away from the cold source. Also shown is the flux for a "normal" neutron guide, coated with Ni ($m = 1$) and the flux at the end of a 6 m long beam tube.

The Be filter is located directly after the exit of the guide, i.e. within the monochromator shielding. The Be is therefore well shielded from the detector. A collimation stage before the monochromator allows to operate TASP under optimum conditions with respect to the conflicting requirements of resolution and intensity. The collimations can be varied between 5'-5'-5'-5' and open-focussing-open-open. A lift allows a choice between vertically focussing graphite or Heusler monochromators. Moreover, a (111) reflection of perfect Si can be used, because the graphite is mounted on Si single crystal with the (111) reflection in the scattering plane, 7° off the $(00L)$ reflection of graphite. Fig. 4 shows the reflectivities of graphite (002) and of one of the best Heusler (111) monochromators measured with unpolarized neutrons. The peak intensity of Heusler is 28% of graphite. In a saturating magnetic field, the ratio increases to $\simeq 34\%$.

The monochromated beam leaves the shielding via a beam plug that contains either permanent magnets or electromagnets that provide a vertical magnetic guide field or a field for remanent supermirror benders that can be used as spin selecting devices. Then no flippers are necessary [5]. The plug can accomodate either a collimator, a bender, or a doubly focussing anti-trumpet. Clearly, a bender is only used in conjunction with a graphite monochromator. The range of monochromator scattering angles is $29° < 2\theta_M < 145°$.

The benders contain glass sheets that are coated with polarizing, remanent supermirror having more than three times the critical angle of bulk Ni ($m > 3$). For geometrical details see Table 2. The transmission of the two types of benders is plotted in Fig. 5. The inset shows a reflectivity profile of a glass sheet of the bender. The number of layers of the coating has been reduced from ideally 450 (see Ref. [5]) to 343 layers in order to achieve a higher production yield for the fabrication of supermirrors.

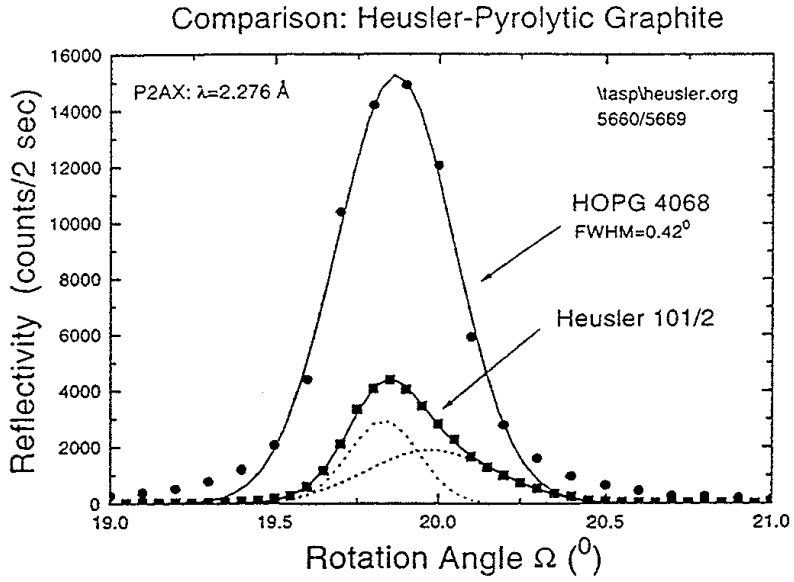

Fig. 4: Reflectivity of graphite (002) (circles) and Heusler (111) (squares). The solid and broken lines indicate Gaussian fits. The monochromator size is 25×50 mm^2.

The bending geometry is such that the polarized neutrons leave the polarizer along the optical axis of the instrument. Therefore, the monochromator must be translated and rotated in such a way that the beam enters the bender properly. These corrections can easily be taken care of by the spectrometer program. Thus the change from unpolarized to polarized beam is trivial: It involves simply the exchange of the exit collimator by a polarizing bender. Moreover, because the bender is positioned inside the monochromator shielding there is little cross talk between external fields at the sample and the spin selecting device.

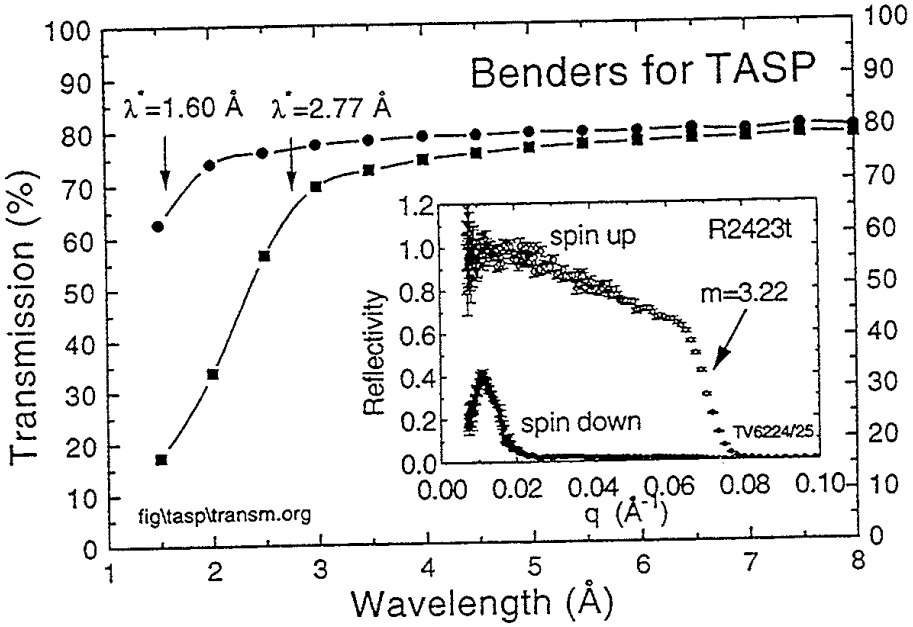

Fig. 5: Transmission of the short (squares) and long (circles) benders. The inset shows the reflectivity profile of an $m = 3$ supermirror.

The doubly focussing trumpet is 1160 mm long and contains supermirror coatings

with $m \simeq 4$. It reduces the horizontal beam size from initially 35 mm to 17.5 mm at the sample position (Fig. 6). The vertical focussing is provided by the monochromator and the vertical section of the trumpet. Experiments at ILL [6] and LLB [7] show that intensity gains $1.5 < G < 7$ can be obtained, depending on the sample geometry, the neutron wavelength and the requirements on the beam divergence.

Table 2: Parameters of the guide and the polarizing benders of TASP. λ^* is the critical wavelength of the bending section.

	neutron guide	short bender	long bender
length (mm)	54 000	290	580
radius of curvature (m)	2063	9.22	31.9
gap (mm)	35	0.95	1.10
m (units of θ_c^{Ni})	2	3	3
λ^* (Å)	1.68	2.77	1.60
Al in the beam (mm)	> 0	3	6

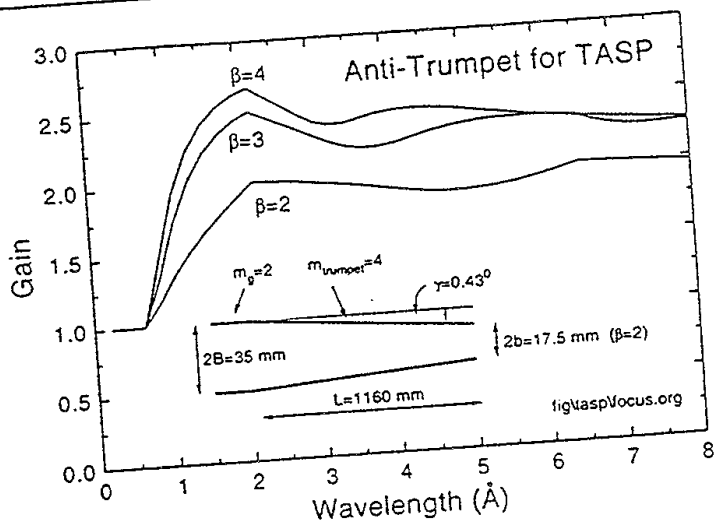

Fig. 6: Calculated flux gains [8] for the horizontally focussing trumpet with $R = 1$ at $m = 4$. β is the ratio B/b. The insert shows a schematics of the part that provides the horizontal focussing.

3. Sample Position

The sample table is equipped with two rotation stages. The primary one determines the orientation of the sample with respect to the incident beam. The second one has been forseen for two purposes:

- Support for a horizontal field magnet, thus $\mathbf{B_h}$ can always be kept parallel to the scattering vector $\mathbf{Q}$, even during inelastic measurements.

- Support for a microstrip detector, thus TASP can be used as a polarized single crystal diffractometer. This option is particularly interesting for investigating incommensurate magnets.

In addition, motorized linear tables for adjusting the sample in the $(x-y)$-plane and two goniometers for tilting the sample are provided.

4. Analyzer and Detector

The shielding of the analyzer housing is composed of shielding blocks that are operated by means of a single compressed air piston. The change between the different horizontally focussing analyzers, graphite and Heusler, is done manually. The inserts have similar dimensions as those in the monochromator shielding, therefore allowing a simple interchange between collimators and polarizing benders. In fact, polarization analysis is most conveniently done by inserting a bender before the detector because i) no corrections for the deviation of the beam have to be made and ii) the cross talk between fields at the sample position and the bender is minimized.

The ^{3}He detector has a diameter of 50 mm and a lenght of 170 mm. Therefore the "vertical focussing" is accomplished by integrating the neutron counts along the vertical dimension of the tube. The detector can be moved inside the detector shielding in order to provide the proper matching sample-analyzer and analyzer-detector distance.

5. Polarization Equipment

In addition to the polarizing and analyzing equipment described above, additional devices are needed to perform a polarized beam experiment. In order to define the quantisation axis for the polarized neutrons, permanent and/or electromagnetic guide fields between monochromator and sample and sample-analyzer-detector are provided. At the sample position Helmholtz coils ($\mathbf{B_v^{max}} = 30$ mT, and $\mathbf{B_h^{max}} = 2$ mT) produce a magnetic guide field that can be oriented in any arbitrary direction with respect to the sample without moving the coils. In particular, the angular access to the sample is larger than 180°, therefore there are no "dark spots" in the beam. This magnet is particularly useful for studying paramagnetic or spin-incoherent scattering.

In addition, for magnetic measurements below the ordering temperature, an asymmetric, superconducting magnet will be available that provides a horizontal field $\mathbf{B_h} = 2$ T and a vertical field $\mathbf{B_v} = 6$ T. The opening angle of the large windows are 150° at the front side and 140° at the back side. The magnet is equipped with a room temperature bore having a diameter of 100 mm. Due to mechanical limitations it is not allowed to operate both fields together.

The polarization of the neutron beams can be changed before and after the sample by means of flat coil spin flippers if no (white beam) spin selective devices are used, thus allowing the measurement of four cross sections σ_{++}, σ_{-+}, σ_{+-}, and σ_{--} [2]. The horizontally wound flipper coil compensates the external guide field and the vertically wound coil ($\rightarrow$ horizontal field) rotates the neutron spin by 180°.

6. Concluding Remarks

TASP is a modern, flexible and compact cold triple-axis spectrometer at the spallation source SINQ. It takes advantage of recent developments in neutron optics, in particular supermirror guides, focussing units as well as remanent spin selective devices. The goal is to provide a very user-friendly polarised beam environment for the investigation of spin dependent cross sections, in particular in the field of magnetism. Special attention has been paid to provide an adequate sample environment.

7. Acknowledgements

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References

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[2] R. Moon, T. Riste, and W. C. Koehler, *Phys. Rev.* **181** (1969) 920 .

[3] Either the sample table, analyzer shielding, or the detector touch the shielding of the ongoing neutron guide.

[4] The neutron energy E(meV) is related to the wavelength λ(Å) by $E = 81.81/\lambda^2$.

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[8] I. S. Anderson, SPIE **983**, 84 (1988).

Appendix: Technical Specifications of TASP

Monochromator scattering angle	$29° < 2\theta_M < 145°$
Analyzer scattering angle	$29° < \lvert 2\theta_A \rvert < 145°$
Neutron energy (PG 002)	$2 \text{ meV} < E_N < 30 \text{ meV}$
	$6.40 \text{ Å} > \lambda > 1.65 \text{ Å}$
	$0.98 \text{ Å}^{-1} < k_N < 3.81 \text{ Å}^{-1}$
Sample scattering angle	$\lvert 2\theta_S \rvert < 150°$
Monochromator size, graphite	$150 \times 125 \text{ mm}^2$ $(w \times h)$ ♠
Monochromator size, Heusler	$100 \times 125 \text{ mm}^2$ $(w \times h)$
Monochromator, perfect Si(111)	5 pc. $150 \times 25 \text{ mm}^2$ $(w \times h)$
Beam size at sample (approx.)	$20 \times 30 \text{ mm}^2$ $(w \times h)$
Monochromator drum diameter	$d = 1.15$ m
Monochromator to sample distance	$1.18 \text{ m} < L_s < 2.93 \text{ m}$
Sample to analyzer distance	$0.82 \text{ m} < L_a < 1.43 \text{ m}$
Analyzer to detector	$0.74 \text{ m} < L_a < 2.55 \text{ m}$
Inpile collimation	$5', 10', 20', 40', 80'$, open
External collimation	$5', 10', 20', 40', 80'$, open
Polarizing benders	$\lambda^* = 1.60$ Å or $\lambda^* = 2.77$ Å
Focussing anti-trumpet	$l = 1160$ mm, supermirror $m \simeq 4$
Detector	^{3}He ($d = 50$ mm, $l = 170$ mm)
Typical spectrometer res.	$\triangle E = 7$ μeV ($E_N \simeq 2$ meV)
(for 20'–20'–20'–20'–20')	$\triangle E = 0.46$ meV ($E_N = 14.7$ meV)
(Vanadium width)	$\triangle E = 1.71$ meV ($E_N = 30$ meV)
pyrolytic graphite filter	$40 \times 130 \times 50$ $(w \times h \times l)$
cooled Be-filter	$40 \times 130 \times 170$, before monochromator
Magnetic fields	2 T horizontal, 6 T vertical
Temperature	$5 \text{ mK} < T < 2000$ K

♠ w: width, h: height, d: diameter, l: length