Neutron Spin-Echo Instrumentation for Magnetic Scattering

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Neutron spin-echo (NSE) spectroscopy is a powerful tool for the study of magnon lifetimes and magnetic critical dynamics. The unique property of NSE is the energy resolution in the \(\mu\)eV range. The first NSE spectrometers were optimized for quasielastic scattering at small momentum transfers and delivered substantial contributions to the understanding of critical dynamics in ferromagnets and dynamic correlations in spin glasses. The subsequent resonant NSE (NRSE) technique extends the parameter range toward large momentum and energy transfers and permits to measure magnon lifetimes across the Brillouin zone. NRSE also comprises the Larmor diffraction (LD) mode with a resolution for lattice spacings and their variance \(\Delta d_{\text{lat}}/d_{\text{lat}}\) of order \(10^{-6}\). LD proves useful to determine magnetostriction effects, small lattice distortions related to magnetic ordering, mosaic spread in crystals, and the size distribution of antiferromagnetic domains. Both typical experiments and the related technical innovation are reviewed and an outlook on future developments is given.

1. Introduction

Neutron spin-echo (NSE) uses the Larmor precession of neutron spins in magnetic fields along the flight paths of the incident and scattered neutron beams as an internal clock to detect small changes of the neutron energy in the scattering process.\(^1,2\) At first glance, NSE looks unsuitable for the study of magnetic dynamics and spin excitations, as related neutron spin flips disturb the Larmor phase. Hence, it is surprising that seminal experiments at the first NSE spectrometer IN11 designed by Mezei at the ILL were studies of the spin relaxation in spin glasses\(^3\) and on critical magnetic dynamics in ferromagnets.\(^4\) Mezei introduced the instrumental configurations “ferromagnetic NSE” (FNSE) and “intensity-modulated NSE” (IMNSE) for NSE experiments on paramagnetic, ferromagnetic, and spin-depolarizing samples, such as ferromagnets with domains\(^5,6\).

Since these early experiments at IN11, NSE blossomed into a rich family of spectrometers and techniques.\(^7\) The direct successors of IN11 use long solenoids to generate the precession fields. These IN11-type spectrometers include the IN15 at the ILL\(^8,9\) and the instruments developed by the Jülich Center for Neutron Science at the NIST (Gaithersburg),\(^10\) the SNS (Oak Ridge),\(^11\) and the MLZ (Garching).\(^12\) They are optimized for ultrahigh resolution at small scattering angles to study slow dynamics at large length scales and made significant contributions to the understanding of spin dynamics in spin glasses and magnetically frustrated systems.\(^13\) Multilane versions of IN11 were designed to gain efficiency by covering large sectors of the scattering angles with detectors. The technical challenge was to generate spacious uniform magnetic precession fields between sample and detectors. The first solution by Farago\(^14\) was the IN11c magnet with \(\approx\)30° coverage of scattering angles, a 30 times increase compared with the IN11 single-detector setup, at the cost of a reduced field homogeneity and hence a reduced resolution. The multilane design was further optimized at the instrument SPAN at HMI (now HZB Berlin). Horizontal Helmholtz coils with opposite current directions generate a radially symmetric horizontal field around the sample. This design allows for a range of scattering angles of nearly 360°.\(^15\) A further innovation for NSE experiments with systems showing complex magnetic order was introduced at SPAN by implementing the cryopad technique at the spin-echo spectrometer.\(^16,17\) With this polarimetric spin-echo technique the matrix elements of the polarization states of the incident and scattered neutron beams are analyzed separately, which is not possible with conventional xyz longitudinal polarization analysis.\(^2,18\)

The method enabled the measurement of spin dynamics across the phase diagram of helimagnetic MnSi.\(^19,20\) SPAN was decommissioned with the shutdown of the BER II reactor but found a successor in the instrument WASP at the ILL.\(^21\)
A second class of NSE spectrometers is based on the neutron-resonance spin-echo technique (NRSE) invented by Golub and Gähler,[22,23] where small radio-frequency (RF) spin flippers define the boundaries of the precession regions. These RF flippers contain a static field and an RF field oscillating at resonance with the Larmor frequency of the neutron spin. NRSE offers many degrees of freedom to adapt the design of the RF flippers to specific spectroscopy tasks. Common to all these designs is the stability of the Larmor phase, which is linked to the inherently stable RF. NRSE permits the implementation of inclined precession field boundaries, a prerequisite for the study of dispersive excitations[24] and for Larmor diffraction (LD).[25] NSE instruments designed for measuring lifetimes of excitations in a wide range of momentum and energy transfers are embedded in a three-axis (TAS) background spectrometer with a crystal monochromator and analyzer, to preselect a region in momentum and energy transfer \((Q, \omega)\). The first instruments of this combined NSE-TAS type were the FLEX-NRSE at HZB,[26,27] TRISP at the MLZ,[28] and ZETA at the ILL.[29] Magnon linewidth data of archetypical antiferromagnets were obtained,[30–32] IN11-type solenoids were implemented in the TASSE project at the TAS spectrometers IN22 at the ILL and PONTA at JAERI (Tokai)[33,34] and gave very good resolution for nondispersive excitations, such as zone-boundary phonons in Ge.[36] A recent development in the field of NSE-TAS uses precession devices (PDs) with static fields (without RF) confined by superconducting Meissner shields to prismatic regions, also referred to as Wollaston prisms.[37,38] First experiments showed a promising performance, both in a measurement of the linewidths and energy renormalization of phonons in Ge[39] and in LD.[40]

The additional degree of freedom to choose different frequencies for the two RF flippers defining the first precession region allows experimenters to generate an intensity-modulated beam with modulation frequencies of several MHz. This is exploited in MIEZE spectrometers.[41] As the intensity modulation is not affected by spin flips from magnetic scattering from spin-depolarizing samples, MIEZE offers the possibility to apply arbitrary fields to the sample, thus facilitating polarization analysis or the use of strong magnets. MIEZE spectrometers are RESEDA at MLZ[42] at VIN-ROSE at J-PARC,[43] and at the OFFSPEC and LARMOR instruments at ISIS.[44–46] The latter also offer the high-resolution spin-echo small-angle scattering (SESANS) mode,[47,48] which was to date mainly used for nonmagnetic scattering, but could be a powerful technique for the study of magnetic domain morphology. The similar SEMSANS method allows to record the small-angle scattering in parallel with 2D imaging.[49,50]

### 2. Brief Introduction to NSE

In this section, we review the properties of NSE. 1) The net Larmor phase of a neutron passing through the setup depends to first order only on the energy transfer \(h\omega\) in the scattering process and is independent of the variance of the incoming neutron wavevector \(k_1\). This also means that the energy resolution is decoupled from the monochromaticity of the incident beam. 2) The quantity measured in NSE is the polarization \(P\) of the neutron beam at the exit of the precession fields. \(P\) is essentially the cosine-Fourier transform in \(\omega\) of the scattering law \(S(Q, \omega)\), the so-called intermediate scattering function in the time domain \(I(Q, \tau)\). We first consider the case of quasielastic scattering (mean energy transfer of zero) and then the general case of a dispersing excitation. Figure 1a shows a generic model of an NSE instrument. Two uniform static (DC) magnetic fields \(B_{1,2}\) of length \(L_{1,2}\) along the paths of the incident and scattered neutron beams with wavenumber \(k_{1,2}\) form the PDs. The fields have flat boundaries perpendicular to the beam axis. The incident beam polarization \(P_1\) is perpendicular to \(B_1\). Inside the PD, the neutron spins precess with Larmor frequency \(\omega_{1,2} = \gamma B_{1,2}\), where \(\gamma = 2.916\text{kHz/Gauss}\) is the "gyromagnetic ratio." The final polarization is given as the average[2]

\[
P = \int S(\omega) \cos(\Delta \phi) d\omega
\]

where \(h\omega\) is the energy transfer and \(S(\omega)\) is the energy-dependent part of the scattering law \(S(Q, \omega)\), where we first neglect the \(Q\) dependence. If the field integrals are equal \((\omega L_{1,2} = \omega_{1,2} L_2)\), the net precession angle is

\[
\Delta \phi = A/k_1 - A/k_2, \quad A = (m/h)\omega_{1,2} L_1
\]

\(m\) is the neutron mass. The minus sign in Equation 2 results from the antiparallel orientation of \(B_1, B_2\). With \(k_2 = \sqrt{k_1^2 - 2m\omega L_1}/h\) and \(k_1 = k_1 + \Delta k_1\), where \(k_1^2\) is the mean and \(\Delta k_1\) is the variance of \(k_1\), the first-order term of Equation (2) is

\[
\Delta \phi = \omega\tau_{\text{NSE}}, \quad \tau_{\text{NSE}} = \frac{m^2\omega_{1,2} L_1}{h^2(k_1^2)}
\]

The constant \(\tau_{\text{NSE}}\) is called "spin-echo time" with values up to \(1\mu s\) in modern IN11-type spectrometers, corresponding to an energy resolution of the order of a few neV. The variance \(\Delta k_1\) would appear in the second-order terms of Equation (3) but is negligible for quasielastic scattering if \(\Delta k_1/k_1 < 0.2\). For the typical Lorentzian \(S(\omega) = \Gamma/|\pi(\Gamma^2 + \omega^2)|\) with linewidth \(\Gamma\) (half-width at half-maximum, Equation 1) gives an exponential decay \(P(\tau_{\text{NSE}}) = \exp(-\Gamma \tau_{\text{NSE}})\). An intuitive physical interpretation of \(\tau_{\text{NSE}}\) in terms of a longitudinal splitting of wave packets related to the up and down spin states is given in other studies.[51,52]

Now we review the general case of NSE applied to dispersive excitations. Here the measurement principle also relies on the linear relation of phase and energy transfer (Equation (3)), but the second-order terms tend to be much larger than in the case of quasielastic scattering. These terms are related to the instrument configuration and sample properties, including beam collimation and monochromatization, scattering geometry, excitation energy, and slope and curvature of the dispersion branch.[53,54] To keep higher orders small compared with the essential first-order \(\omega\tau_{\text{NSE}}\), the variance of \(k_{1,2}\) has to be limited using a (crystal) monochromator (M) and analyzer (A), so that the spin-echo PDs are embedded in a three-axis spectrometer (TAS). The instrumental resolution of this so-called "background" TAS is an ellipsoid-shaped function \(R(\mathbf{Q}, \omega)\) (Figure 2) giving the...
probability to detect a scattering event at \((Q, \omega)\) located on a dispersion sheet around a central value \((Q_0, \omega_0)\).

The dark blue disks sketched inside the ellipsoid are the planes of constant spin-echo phase, which are tuned by proper choice of the PD parameters to be oriented tangential to the dispersion surface. All scattering events on such a plane will accumulate the same Larmor phase \(\Delta \phi\), and the phase of other scattering events inside the region defined by the ellipsoid will vary proportional to \(\hbar \omega\), independent of \(Q\). The basic NSE instrument with TAS background spectrometer is shown in Figure 1c, where besides the crystal monochromator (M) and AN (A), the variable inclination angles \(\theta_{1,2}\) of the field boundaries are introduced as additional parameters. \(n_{1,2}\) are unit vectors normal to the field boundaries. The instrumental tuning conditions for the field inclination at the nominal excitation \((Q_0, \omega_0)\) depend on the slope of the dispersion \(\nabla q \omega_0(q_0)\).

\[
n_{1,2} = \frac{N_{1,2}}{N_{1,2}} \quad \text{with} \quad N_{1,2} = \frac{\hbar}{m} k_{1,2} - \nabla q \omega_0(q_0) \quad \text{and} \quad N_{1,2} = |N_{1,2}|
\]

and

\[
\frac{\omega_{1,2}L_1}{\omega_{1,2}L_2} = \frac{N_{1}(k_{1} \cdot n_{1})^2 \cos \theta_2}{N_{2}(k_{2} \cdot n_{2})^2 \cos \theta_1}
\]

Definitions of \(\theta_{1,2}\) are shown in Figure 1c. The spin-echo time is then
the initial beam polarization
parallel, with a small longitudinal guide field antiparallel (in the sample region. The reason for the parallel alignment is the effective Larmor frequency and the phase stability. A further amplification with an effective Larmor frequency of $4\omega_{1,2}$ is obtained in the “bootstrap” setup with double RF flippers and antiparallel DC fields (Figure 1e). Besides a higher effective Larmor frequency, the latter has the advantage of very low DC stray fields outside the flippers, such that the whole beam path between the $\pi/2$ flippers can be housed inside a mu-metal magnetic shield to reduce the sensitivity to external fields. Inclined field boundaries are easily achieved by rotating the RF flippers (Figure 1f). Such RF bootstrap flippers with DC fields transverse to the beam axis are used at the TAS spectrometers TRISP, ZETA, and FLEXX (decommissioned). One disadvantage of the transverse field flipper type is that the neutron beam has to transmit the windings of the coils, to minimize absorption, the thickness of the wires has to be minimized, but this also increases resistive heating, such that the DC field and $\tau_{\text{NSE}}$ are limited to significantly smaller values than those reachable by the IN11-type solenoid design.

A solution to increase the resolution given by the maximum field in NRSE spectrometry is the so-called longitudinal (L)-NRSE technique used at the RESEDA spectrometer (Figure 1g), where large DC fields are generated parallel to the beam axis, either by short solenoids or by Helmholtz coils, such that the beam only transmits the winding of the RF coil. The precession field strength obtained by the first-generation L-NRSE is comparable with that of the IN11-type spectrometers, but the latter still can handle much larger beam cross sections. L-NRSE has many degrees of freedom for optimizing the performance, but it is limited to nondispersive excitations, as there is no option to incline the field boundaries.

The RF flippers at the LARMOR and OFFSPEC instruments at ISIS use transverse DC fields generated by iron-yoke electromagnets and RF fields longitudinal to the beam axis, such that the beam transmits the coil freely without touching any wires. The beam cross section for these coils is limited, but the design is very good for applications in reflectometry and SESANS, where additional SANS in the coils has to be avoided. Wedge-shaped pole pieces on the electromagnets also allow for inclined field boundaries.

A novel PD design is based on superconducting Wollaston prisms with transverse DC fields, as shown in Figure 1h. All field sections $B_{1,5}$ are tunable without significant crosstalk between them. Although the geometry is fixed, arbitrary effective field inclination angles can be set. Thus, the device is useful for the study of excitations and for LD. The performance of the first prototype devices is already close to the transverse RF flippers, and recently RF coils were incorporated in these superconducting devices to further enhance the effective Larmor frequency and the phase stability.
MIEZE (Figure 1i) is basically a time-of-flight (TOF) method, where fast-intensity modulation of a neutron beam is generated by RF flippers and a subsequent AN. The resulting intensity modulation reaches frequencies in the MHz range, whereas mechanical choppers can at best reach a few kHz. The challenge is the detection of such a fast-intensity modulation, which is smeared out by the variance in $\Delta k_i$. Assume for example typical cold neutrons of wavelength $\lambda = 4 \text{ Å}$ and velocity $v = 1000 \text{ m s}^{-1}$ modulated at 1MHz and a monochromaticity of $\Delta k_i/k_i = 0.05$. After $\approx 20$ modulation periods corresponding to a neutron path of 20 mm, the modulation is averaged to zero. A solution to recover the fast-intensity modulation at a focal point corresponding to the location of the neutron detector was first found by Golub and Gähler for a mechanical chopper system, called FOTOF, and later transferred to RF flippers. Figure 1i shows the basic MIEZE configuration. Two RF flippers upstream the sample are operated at different fields $B_{1,2}$ with resonant frequencies $\omega_{1,2}$, with $\omega_{1} > \omega_{2}$. Then, at the exit of RF flipper 2, the polarization is modulated by $\Delta \omega_M = 2(\omega_{12} - \omega_{11})$ (the factor 2 applies for single RF flippers), and the modulation recovers at the focal plane and the detector, respectively. The range of $\Delta \omega_M$ is limited by the coupling to the focal length $L_2$ via the ratio and difference of $\omega_{1,2}$. An additional DC field $B_i$ in between the RF flippers allows for independent tuning of $L_2$ and for a wider range of $\Delta \omega_M$. After passing the $\pi/2$ flipper and polarization analyzer (AN), the modulation of the polarization is converted to an intensity modulation $I(t) \sim 1 + C \sin(\Delta \omega_M t)$, with

$$C(\tau_M) = \int S(\omega) \cos(\omega \tau_M) d\omega \quad \text{with} \quad \tau_M = \frac{m \Delta \omega_M L_2}{\hbar k_i^3} \quad \text{(8)}$$

The intensity modulation is not affected by spin flips in the sample, such that investigation of ferromagnetic samples and application of high magnetic fields is possible. One limitation of MIEZE is the sensitivity to path length variation of the neutron trajectories, which increases with the scattering angle and the sample size. Hence, MIEZE is more powerful for small-scattering angles. At larger scattering angles, very good resolution is only achieved if the sample size parallel to $Q$ is small (in the order of 1 mm), whereas the sample dimension perpendicular to $Q$ has little effect on the path length. As the AN is placed upstream of the sample, the beam incident on the sample is polarized, such that both longitudinal polarization analysis and polarimetry can be applied.

LD is a high-resolution technique closely related to spin echo. First, LD is based on Larmor precession in DC fields or RF flippers with inclined field boundaries and is thus readily available on N(R)SE-TAS instruments. Second, LD delivers information necessary to interpret and analyze spectroscopic NSE data, including accurate thermal expansion data, information about structural distortions and magnetostriiction related to magnetic ordering, and mosaicity and microstrains related to crystal quality. The characteristic limitation of conventional diffractometers imposed by the inverse proportionality between intensity and resolution is not effective in LD, and excellent momentum resolution without excessive loss of intensity is achieved. In this respect, LD is similar to NSE, where the energy resolution is decoupled from the monochromaticity of the incident neutron beam. The drawing in Figure 3a shows the field configuration proposed by Rekveldt, which comprises two DC fields $B_{1,2}$ with boundaries parallel to the lattice planes or perpendicular to the reciprocal lattice vector $G_{hkl}$. Note that there is no $\pi$ flipper, such that the phases add. The phase is proportional to the transition time $t = mL/(\hbar k_i)$ the neutron spends in the field regions. The momentum perpendicular to the field boundary $k_z = G_{hkl}/2 = \pi/d_{hkl}$ is selected by the Bragg reflection, so that all neutrons reflected at the lattice planes $d_{hkl}$ acquire the same phase, independent of the Bragg angle.

$$\phi_{LD} = \frac{2m \omega_{AN}}{\hbar \pi} d_{hkl} \quad \text{(9)}$$

A variation of $d_{hkl}$, for example, by thermal expansion, is measured by tracking the phase shift $\Delta \phi(T) = \phi_{LD} \times \epsilon_{hkl}$ versus the temperature $T$, where

![Figure 3. Larmor diffractometer layouts.](Image)

**Figure 3.** Larmor diffractometer layouts. a) Standard LD. b) Single-arm LD. c) MIEZE LD. PO: polarizer; AN: polarization analyzer; DET: neutron detector; $\pi/2$ flipper.
\[ \epsilon_{hkl} = \frac{d_{hkl}}{d_{hkl}^{0}} - 1 \]  
\(d_{hkl}^{0}\) is the mean or unperturbed value of \(d_{hkl}\). \(d_{hkl}\) is typically spread, for example, by the effect of microstrains. Then the phase is also spread as

\[
\Delta \phi_{\text{LD}} = \phi_{\text{LD}}^{0} \times \epsilon_{hkl} \tag{11}
\]

\(\phi_{\text{LD}}^{0}\) is related to \(d_{hkl}^{0}\) via Equation 9. The final beam polarization is given by the average

\[
P_{\text{LD}}(\phi_{\text{LD}}) = \langle \cos(\Delta \phi_{\text{LD}}) \rangle = \int D(\epsilon_{hkl}) \cos(\phi_{\text{LD}} \epsilon_{hkl})d\epsilon_{hkl} \tag{12}
\]

\(D\) is the distribution function of \(\epsilon_{hkl}\). The benefit of using two PDs is not obvious for LD on single crystals, except for the gain factor 2 in Equation 9, but becomes apparent for mosaic or polycrystalline samples, where the lattice planes deviate from the ideal orientation parallel to the field boundaries. In this case, the Larmor phases in the first and second PD are different, but the sum \(\phi_{\text{LD}}\) stays constant, such that the resolution is not limited by the crystal mosaic. For powder samples, the resolution might be degraded by parasitic small-angle scattering of the neutrons inside the sample, but this effect is minimized by proper design of the shape of the sample containers.\[72,73\] As LD is difficult to integrate into conventional powder diffractometers with multiaxis detectors, Rekvelt suggested the configuration in Figure 3b using only one PD upstream of the sample, at the cost of a reduced resolution.\[72,73\] Such an instrument could enhance the resolution of powder diffraction by one order of magnitude toward \(\epsilon_{hkl} \sim 10^{-5}\), that is about one order of magnitude less than for the standard LD configuration with two PDs. Below we will discuss a combination of LD and MIEZE for the design of future instruments.

### 4. Spin-Echo View of Magnetic Scattering

In this section, we discuss the spin-flip processes related to magnetic scattering in view of N(R)SE. This discussion is valid for all types of spin-echo spectrometers, but there are also differences. At NSE-type spectrometers with DC precession fields there is a small guide field at the sample, which also defines a quantization axis for the spin, whereas at NRSE-TAS instruments, the sample is typically located in a zero-field region, and the spin projection on a quantization axis given by the guide field occurs at the transition from the zero field to the guide field region of the AN. Here we will use the geometry of the TRISP spectrometer, as the experimental examples shown in the following section were all measured at this spectrometer. In contrast to the usual 1D polarization analysis,\[58\] where the polarization of the incident neutrons is defined by a guide field at the sample, in NSE, the phases \(\phi_{1}\) of the spins of the incident neutrons \(s_{1}\) are spread by \(\Delta \phi_{1}\) within the xy plane (“precession plane” \(\perp B_{y}\)) due to the variance of \(k_{1}\), where typically \(\Delta \phi_{1} \gg 2\pi\) (Figure 4).

Mezei pointed out that the magnetic fluctuations \(M_{x}\) and \(M_{z}\) parallel and perpendicular to the xy-precession plane have to be distinguished.\[14\] As the x-axis is defined to be parallel \(Q\), the component \(M_{y}\) does not contribute to the scattering cross section. The spin flips can be considered as a rotation by \(\pi\) on a cone defined by the angle between \(s_{1}\) and the magnetic fluctuations

![Figure 4. Spin flips and Larmor phase at the sample. The spins of the incident beam are spread within the xy-plane, the precession plane \(\perp B_{y}\), with \(x||Q, z\) is vertical. The magnetic fluctuations \(M_{y}, M_{z} \perp Q\) contribute to the scattering cross section. The spin \(s_{1}\) with \(\phi_{1}\) of an incident neutron is flipped to \(s_{2}\) or \(s_{3}\) by \(M_{y}\) or \(M_{z}\), respectively. The corresponding phases are \(\phi_{2} = \pi - \phi_{1}\) and \(\phi_{3} = \pi + \phi_{1}\).](image)

\(M_{y}\) or \(M_{z}\), which flip \(s_{1}\) to \(s_{2}\) or \(s_{3}\), respectively. The related phases are \(\phi_{2} = \pi - \phi_{1}\) or \(\phi_{3} = \pi + \phi_{1}\). \(\phi_{2}\) already includes the sign change of \(\phi_{1}\) and thus effectively inverts the direction of the first precession region, whereas \(\phi_{3}\) includes only an additional phase \(\pi\) but no sign inversion of \(\phi_{1}\). Thus, to fulfill the echo condition, for the \(M_{y}\) fluctuations, the polarity of the PDs is chosen antiparallel or a \(x\) flipper is used as in the case of nonmagnetic scattering, whereas for the \(M_{z}\) fluctuations, the PDs are poled parallel or the \(x\) flipper is omitted. If both \(M_{y}\) and \(M_{z}\) are present, the configuration giving the better signal amplitude is chosen experimentally. For large \(\tau_{\text{NSE}}\), the neutrons scattered by the fluctuations fulfilling the echo condition contribute to the polarized signal, whereas the other fraction generates a nonpolarized background reducing the signal polarization. In this case, Equation 1 applies with a constant prefactor \(P_{b}\), where \(P_{b} = 0.5\) for equal population of \(M_{y}\) and \(M_{z}\). For small \(\tau_{\text{NSE}}\), spin flips from \(M_{y,z}\) give oscillating signals, which require a numerical analysis beyond the simple Equation (1), as demonstrated in the example on critical scattering below.

In ferromagnetic samples, the neutron spins acquire an additional Larmor phase with a large variance depending on the domain sizes and orientations,\[54\] such that all spin-echo-related phase information is lost. Farago introduced an IMNSE configuration with additional POs up- and downstream of the sample, which recover 50% of the spin-echo signal\[5\] at the cost of a 75% intensity reduction. The principle is that across the sample the Larmor phase is converted to an intensity modulation \(I(\Delta k_{1})\). This IMNSE scheme was also used to combine polarimetric analysis based on cryopad with NSE.\[16,17,20\] The MIEZE method also is not affected by spin flips, as the Larmor phase is converted to an intensity modulation \(I(t)\), in analogy to IMNSE. In addition, either conventional 1D polarization analysis or polarimetry could be combined with MIEZE but limited to dispersionless excitations.

### 5. Examples from TRISP

Here we show examples focusing on the present potential of NRSE-TAS at the TRISP spectrometer. These include the textbook case of antiferromagnetic (AF) magnons in 3D and...
quasi-2D spin-5/2 systems MnF2 and Rb2MnF4, respectively, the
critical scattering in these compounds for $T \geq T_N$, spin excita-
tion linewidths in a 1D chain material, and examples from LD
related to magnetic ordering.

5.1. Magnon Lifetimes and Critical Dynamics in 2D and 3D
Antiferromagnets

Rb2MnF4 and MnF2 are textbook examples for 2D and 3D
Heisenberg antiferromagnets with a small uniaxial anisotropy
resulting from dipolar spin−spin interactions. Previous calcula-
tions of the magnon linewidth (inverse lifetime) based on four-
magnon scattering and linewidth data from conventional neutron
spectroscopy showed considerable disagreement. The discrepancy
resulted both from necessary approximations in the analytical
calculations and from limited resolution in neutron spectroscopy.
In other studies, NRSE data with a signifi-
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High-resolution NRSE data for the magnon linewidths were
collected both for Rb₂MnF₄ and for MnF₂ across the Brillouin
zone (BZ), in the AF-ordered state between 3 K and 0.6 $T_N$
($T_N$ is 38.4 K for Rb₂MnF₄ and 67.6 K for MnF₂). Both systems
have a tetragonal structure, and the dominating magnetic inter-
action is the exchange coupling between the $s = 5/2$ Mn$^{2+}$ spins.
The uniaxial AF spin alignment along the crystallographic c-axis
is due to an uniaxial anisotropy arising from dipole−dipole
interactions. Referring to Figure 4, with alignment of the crystal-
lographic c-axis ||z, only the $M_z$ fluctuations contribute to the
scattering cross section. This implies that the parallel field
configuration of the spectrometer, corresponding to NSE without
$\pi$ flipper, gives the echo condition. Raw spin-echo data from
MnF₂ are shown in Figure 5. The curves are well described
by exponentials $P \propto \exp(-\Gamma_{\text{NSE}} h)$ (straight lines in the semilog
plot), corresponding to Lorentzian $S(\omega)$. The difference in $\Gamma$
between the central and the lower and upper curve is as small
as $\pm 3 \mu$eV, reflecting the good energy resolution of the NRSE
technique. These raw data are then corrected for the resolution
$P(\tau_{\text{NSE}})$ according to Equation 6 using the formalism of the study
by Habicht et al.[33] including the slope and curvature of the dis-

ciprodipole scattering from
Figure 6c. This contribution was identi-

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5.2. Spin Excitations in a 1D Quantum Magnet

In the standard picture, a spin excitation decays exponentially in the
time domain by collisions with other excitations. This exponential
decay leads to a Lorentzian lineshape $S(\omega)$ in energy. With increasing temperature, the collisions become more fre-
frequent, and the width $\Gamma$ of the Lorentzian increases. This simple
picture fails in 1D systems with hard-core interactions, where
strong deviations from the exponential decay and thus non-
Lorentzian asymmetric lineshapes in energy are expected.[78]
A model system for such a 1D spin-1/2 antiferromagnet is

![Figure 5. Raw spin-echo polarization data from MnF2. Reproduced with permission.](image-url)
copper nitrate \([\text{Cu(NO}_2\cdot 2.5\text{D}_2\text{O}}\). TOF neutron spectroscopy found the expected asymmetric \(S(\omega)\), but in view of the elaborate data analysis including deconvolution with the TOF instrumental resolution on a strongly sloping signal background, a confirmation of the results by the independent NRSE was suggested.\(^{[78]}\) NRSE offers two advantages for this study, including the direct observation of the decay in the time domain, and the insensitivity to the sloping background, which only gives a constant factor reducing \(P(\text{NSE})\). In contrast to the majority of \(N(R)SE\) experiments, where only the magnitude of \(P\) is analyzed, here also the phase of \(P\) (Figure 8b) was included in the data analysis, as the latter also carries information about the excitation energy and lineshape.\(^{[80,81]}\) The resulting \(S(\omega)\) in Figure 8a shows a clear evolution of the asymmetric broadening with temperature and thus confirms previous TOF data.

5.3. Magnetic Ordering and Structural Effects

Ordering phenomena of the electron system usually cause a response of the crystal lattice or are vice versa triggered by a
structural transition. The structural effects observable by LD include anomalies in the thermal expansion, structural transitions, small distortions of the structure, and, on a mesoscopic scale, the formation of structural and magnetic domains. Thermal expansion is usually measured by capacitive dilatometry with a resolution superior to LD. The latter is unique if conducting dilatometry is challenging, as in the case of high pressures and high temperatures. LD moreover is sensitive to specific crystallographic directions by selection of appropriate Bragg peaks, even in polycrystalline samples. Examples for LD experiments at high pressures include a study of the thermal expansion of MnSi\(^{[82]}\) to elucidate the nature of a non-Fermi liquid state and a study related to the hidden-order phase in URu\(_2\)Si\(_2\).\(^{[83]}\) LD studies on iron pnictides, partially under uniaxial pressure, helped to elucidate the interplay between the orthorhombic-to-tetragonal phase transition, AFM ordering, and superconductivity.\(^{[84–86]}\) A further example is the structural phase transition in an iron pnictide, where the expected orthorhombic splitting of a Bragg peak is not visible in conventional diffraction due to the large intrinsic width of the peaks, whereas it was unambiguously detected by LD.\(^{[87]}\)

Finally, we discuss an example of mesoscopic structural domains in undoped, AFM YBa\(_2\)Cu\(_3\)O\(_{6.0}\). The data in Figure 9 show the polarization \(P(\phi_{LD})\) for the (220) and (200) Bragg peaks above and below the Néel temperature \(T_N = 420\)K. The data \(P(\phi_{LD})\) are well described by Equation 12, assuming Gaussian distributions \(D\). The widths look quite different, but have the same ratio \(\sqrt{2}\) as the corresponding reciprocal lattice vectors, and are thus consistent with square-shaped domains of characteristic width \(L_j = 370\) nm in the CuO\(_2\) planes. The domain size in the perpendicular direction obtained from the (006) data is \(L_\perp = 390\) nm. This structural domain formation probably results from impurities and associated microstrains. Below \(T_N\) the domain shape stays unchanged but shrinks by about 10\% as a consequence of magnetostriction effects. The characteristic width of the AFM domains of 240 nm is smaller than those of the structural domains, consistent with the assumption that structural domain boundaries disrupt magnetic order.

6. Conclusion

Neutron spin echo offers versatile instrumental configurations for the study of spin excitations and structural effects related to magnetic ordering. Experimentally challenging is the study of neutron spin-depolarizing ferromagnetic samples with domains or samples in high fields, both for spectroscopy and LD. There are two solutions for spectroscopy, but both are associated with severe limitations. The IMNSE configuration requires an additional PO/AN pair close to the sample, at the cost of an intensity loss of at least 75\%. MIEZE, in contrast, needs no additional POs, and magnetic fields of 17 Tesla were applied to the sample, but the resolution decreases with increasing momentum transfer due to an increasing variance of the path lengths of neutron trajectories across the sample. In addition, there is at present no solution allowing applications of MIEZE to dispersive excitations.

Figure 8. a) Linewidth of the one-magnon mode in copper nitrate at the minimum of the dispersion corresponding to \(Q = (101)\). b) Phase of \(P(\tau_{NSE})\). Reproduced with permission.\(^{[80]}\) Copyright 2016, APS.

Figure 9. LD polarization data versus total Larmor phase for the (220) and (200) Bragg peaks in YBa\(_2\)Cu\(_3\)O\(_{6.0}\), at temperatures below and above \(T_N = 420\) K. Inset: (220), (006), and \((\frac{1}{2} \frac{1}{2} \frac{5}{2})\) at \(T = 40\) K. Reproduced with permission.\(^{[90]}\) Copyright 2016, APS.
In the case of LD, the situation is more favorable. There are several solutions to cope with spin-depolarizing samples, all with their specific drawbacks. First, there is Rekveldt’s single-arm LD (Figure 3b). It was originally designed for implementing LD at powder diffractometers with multimeter detectors, and it is insensitive to depolarizing samples. The main limitation is that the resolution (Figure 3a) is reduced by one order of magnitude compared with full LD and strongly depends on the scattering angle and beam collimation. These disadvantages are partially compensated by combining MIEZE with LD (Figure 3c). The resolution of this setup approaches the one of full LD for small samples of dimension ≈1 mm but also depends on path length variance in the sample.

Currently, the first dedicated Larmor diffractometer LADIFF is under construction at the MLZ, using the main components of the TAS FLEXX from HZB. LADIFF is based on transverse RF flippers and will offer the aforementioned options for depolarizing samples in strong magnetic fields.

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Conflict of Interest

The authors declare no conflict of interest.

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[1] F. Mezei, Z. Phys. A 1972, 255, 146.
[2] Neutron Spin Echo (Ed: F. Mezei), Lecture Notes in Physics, Vol. 128, Springer, Berlin 1980.
[3] F. Mezei, A. Muranji, J. Magn. Magn. Mater. 1979, 14, 211.
[4] F. Mezei, Phys. Rev. Lett. 1982, 49, 1096.
[5] B. Farago, F. Mezei, Physica B+C 1986, 136, 100.
[6] F. Mezei, G. Drabkin, A. Ioffe, Physica B 2001, 297, 9.
[7] Neutron Spin Echo Spectroscopy (Eds: F. Mezei, T. Gutterlet, C. Pappas), Lecture Notes in Physics, Vol. 601, Springer, Berlin 2003.
[8] P. Schleger, G. Ehlers, A. Kollmar, B. Alefeld, J. Barthelmy, H. Casalta, B. Farago, P. Giraud, C. Hayes, C. Lartigue, F. Mezei, D. Richter, Physica B: Conden. Matter 1999, 266, 49.
[9] B. Farago, P. Falus, I. Hoffmann, M. Gradzielski, F. Thomas, C. Gomez, Neutron News 2015, 26, 15.
[10] N. Rosov, S. Rathgeber, M. Monkenbusch, in Scattering From Polymers, ACS Symposium Series, Vol. 739, American Chemical Society, Washington, DC 2000, pp. 103–116.
[11] M. Ohl, M. Monkenbusch, N. Arend, T. Kozielewski, G. Vehres, C. Tiemann, M. Butzek, H. Soltner, U. Giesen, R. Achten, H. Stelzer, B. Lindenau, A. Budwig, H. Kleines, M. Drochner, P. Kämmenling, M. Wagener, R. Maller, E. Iversen, M. Sharp, D. Richter, Nucl. Instrum. Methods A 2012, 696, 85.
[12] S. Pasini, O. Holderer, T. Kozielewski, D. Richter, M. Monkenbusch, Rev. Sci. Instrum. 2019, 90, 043107.
[13] G. Ehlers, J. Phys.: Condens. Matter 2006, 18, R231.
[14] B. Farago, Physica B 1997, 241–243, 113.
[15] C. Pappas, C. Kali, T. Krist, P. Böni, F. Mezei, Phys. B 2000, 283, 265.
[16] C. Pappas, E. Leïliève-Berna, P. Bentley, E. Bourget-Lami, E. Moskvin, M. Thomas, S. Grigoriev, V. Dyadkin, Nucl. Instrum. Methods A 2008, 592, 420.
[17] E. Leïliève-Berna, P. Bentley, E. Bourget-Lami, M. Thomas, C. Pappas, R. Kischnik, E. Moskvin, Physica B 2009, 404, 2624.
[18] R. M. Moon, T. Riste, W. C. Koehler, Phys. Rev. 1969, 181, 920.
[19] C. Pappas, E. Leïliève-Berna, P. Bentley, P. Falus, P. Fouquet, B. Farago, Phys. Rev. B 2011, 83, 224405.
[20] L. J. Bannenberg, K. Kakurai, P. Falus, E. Leïliève-Berna, R. Dalglish, C. D. Dewhurst, F. Qian, Y. Onose, Y. Endoh, Y. Tokura, C. Pappas, Phys. Rev. B 2017, 95, 144433.
[21] P. Fouquet, G. Ehlers, B. Farago, C. Pappas, F. Mezei, J. Neutron Res. 2007, 15, 39.
[22] R. Gähler, R. Golub, J. Phys. (France) 1988, 49, 1195.
[23] R. Golub, R. Gähler, Phys. Lett. A 1987, 123, 43.
[24] F. Mezei, in Neutron Inelastic Scattering, IAEA, Vienna 1978, p. 125.
[25] M. T. Revkelt, T. Keller, R. Golub, Europhys. Lett. 2001, 54, 342.
[26] T. Keller, R. Golub, F. Mezei, R. Golub, Physica B 1997, 241–243, 101.
[27] F. Groitl, T. Keller, D. L. Quintero-Castro, K. Habicht, Rev. Sci. Instrum. 2015, 86, 025110.
[28] T. Keller, K. Habicht, H. Klann, M. Ohl, H. Schneider, B. Keimer, Appl. Phys. A 2002, 74, s332.
[29] N. Martin, L.-P. Regnault, S. Klimko, J. Lorenzo, R. Gähler, Physica B 2011, 406, 2333.
[30] S. Bayrakci, T. Keller, K. Habicht, B. Keimer, Science 2006, 312, 1926.
[31] B. Nafrádi, T. Keller, H. Manaka, A. Zheludev, B. Keimer, Phys. Rev. Lett. 2011, 106, 177202.
[32] A. L. Chernyshev, M. E. Zhitomirsky, N. Martin, L.-P. Regnault, Phys. Rev. Lett. 2012, 109, 097201.
[33] C. Zeyen, J. Phys. Chem. Solids 1999, 60, 1573.
[34] C. M. E. Zeyen, P. C. Rem, Mass. Sci. Technol. 1996, 7, 782.
[35] M. Nishi, K. Kakurai, Physica B 2002, 311, 70.
[36] J. Kulda, A. Debernardi, M. Cardona, F. de Geuser, E. E. Hailer, Phys. Rev. B 2004, 69, 045209.
[37] F. Li, S. R. Parnell, T. Wang, D. V. Baxter, R. Pynn, J. Phys. Conf. Ser. 2016, 711, 012015.
[38] F. Li, R. Pynn, J. Appl. Crystallogr. 2014, 47, 1849.
[39] F. Li, J. Shen, S. R. Parnell, A. N. Thaler, M. Matsuda, T. Keller, O. Delaire, R. Pynn, J. A. Fernandez-Baca, J. Appl. Crystallogr. 2019, 52, 755.
[40] F. Li, H. Feng, A. N. Thaler, S. R. Parnell, W. A. Hamilton, L. Crow, W. Yang, A. B. Jones, H. Bai, M. Matsuda, D. V. Baxter, T. Keller, J. A. Fernandez-Baca, R. Pynn, Sci. Rep. 2017, 7, 865.
[41] M. Krautloher, J. Kindervater, T. Keller, W. Häussler, Rev. Sci. Instrum. 2016, 87, 125110.
[42] H. Endo, T. Oda, M. Hino, T. Hosobata, Physica B 2019, 564, 91.
[43] R. Dalglish, S. Langridge, J. Plomp, V. de Haan, A. van Well, Physica B 2011, 406, 2346.
[44] J. Plomp, V. de Haan, R. Dalglish, S. Langridge, A. van Well, Thin Solid Films 2007, 515, 5732.
[45] N. Geerts, S. R. Parnell, M. A. Thijs, A. A. van Well, C. Franz, A. L. Washington, D. Raspino, R. M. Dalglish, J. Plomp, Rev. Sci. Instrum. 2019, 90, 125101.
[46] T. Keller, R. Gähler, H. Kunze, R. Golub, Neutron News 1995, 6, 16.
[47] M. Revklivt, Nucl. Instrum. Methods B 1996, 114, 366.
[49] M. Stroblij, M. Sales, J. Plomp, W. G. Bouwman, A. S. Tremsin, A. Kaestner, C. Pappas, K. Habicht, Sci. Rep. 2015, 5, 16576.

[50] M. Sales, J. Plomp, K. Habicht, A. Tremsin, W. Bouwman, M. Stroblij, Rev. Sci. Instrum. 2016, 87, 063907.

[51] R. Gähler, R. Golub, K. Habicht, T. Keller, J. Felber, Physica B 1996, 229, 1.

[52] J. Felber, R. Gähler, R. Golub, K. Prechtel, Physica B 1998, 252, 134.

[53] K. Habicht, T. Keller, R. Golub, J. Appl. Crystallogr. 2003, 36, 1307.

[54] F. Groitl, T. Keller, K. Habicht, J. Appl. Crystallogr. 2018, 51, 818.

[55] C. Franz, S. Säubert, A. Wendl, F. X. Haslbeck, O. Soltwedel, J. K. Jochum, L. Spitz, J. Kindervater, A. Bauer, P. Böni, C. Pfeiferer, J. Phys. Soc. Jpn. 2019, 88, 081002.

[56] T. Rekveldt, W. Kraan, Nucl. Instrum. Methods A 2011, 629, 239.

[57] J. Major, H. Dosch, G. Felcher, K. Habicht, T. Keller, S. te Velthuis, A. Vorobiev, M. Wahl, Physica B 2003, 336, 8.

[58] G. P. Felcher, S. G. E. te Velthuis, J. Major, H. Dosch, C. Anderson, K. Habicht, T. Keller, in Advances in Neutron Scattering Instrumentation, Proc. SPIE Vol. 4785 (Eds: I. S. Anderson, B. Guérard), International Society for Optics and Photonics, SPIE, Washington, DC 2002 pp. 164–173.

[59] J. Major, A. Vorobiev, A. Rühm, R. Maier, M. Major, M. Mezger, M. Nüille, H. Dosch, G. P. Felcher, F. Falus, T. Keller, R. Pynn, Rev. Sci. Instrum. 2009, 80, 123903.

[60] M. T. Rekveldt, W. G. Bouwman, W. H. Kraan, O. Uca, S. V. Grigoriev, K. Habicht, T. Keller, in Elastic Neutron Scattering Measurements Using Lamor Precession of Polarized Neutrons, Springer Berlin Heidelberg, Berlin, Heidelberg 2003, pp. 87–99.

[61] W. G. Bouwman, J. Plomp, V. O. de Haan, W. H. Kraan, A. A. van Well, K. Habicht, T. Keller, M. T. Rekveldt, Nucl. Instrum. Methods A 2008, 586, 9.

[62] F. Li, R. Dadisman, D. C. Wasilkoski, Nucl. Instrum. Methods A 2020, 955, 163300.

[63] R. Gähler, R. Golub, Z. Phys. B 1984, 56, 5.

[64] J. K. Jochum, A. Wendl, T. Keller, C. Franz, Meas. Sci. Technol. 2019, 31, 035902.

[65] S. Säubert, J. Kindervater, F. Haslbeck, C. Franz, M. Skoulatos, P. Böni, Phys. Rev. B 2019, 99, 184423.

[66] F. Haslbeck, S. Säubert, M. Seifert, C. Franz, M. Schulz, A. Heinemann, T. Keller, P. Das, J. D. Thompson, E. D. Bauer, C. Pfeiferer, M. Janoschek, Phys. Rev. B 2019, 99, 014429.

[67] J. Kindervater, N. Martin, W. Häußler, M. Krautloher, C. Fuchs, S. Mühlbauer, J. A. Lim, E. Blackburn, P. Böni, C. Pfeiferer, EPJ Web Conf. 2015, 83 03008.

[68] G. Brandl, R. Georgii, W. Häußler, S. Mühlbauer, P. Böni, Nucl. Instrum. Methods A 2011, 654, 394.

[69] T. Weber, G. Brandl, R. Georgii, W. Häußler, S. Weichselbaumer, P. Böni, Nucl. Instrum. Methods A 2013, 713, 71.

[70] M. T. Rekveldt, Physica B 2000, 276–278, 55.

[71] T. Keller, P. Fabrykiewicz, R. Przeniosło, I. Sosnowska, B. Keimer, J. Appl. Crystallogr. 2020, 53, 88.

[72] M. T. Rekveldt, J. Plomp, A. A. van Well, J. Appl. Crystallogr. 2014, 47, 436.

[73] A. van Well, M. Rekveldt, J. Phys. Conf. Ser. 2017, 862 012029.

[74] M. T. Rekveldt, Z. Phys. 1973, 259, 391.

[75] S. P. Bayrakci, D. A. Tennant, P. Leininger, T. Keller, M. C. R. Gibson, S. D. Wilson, R. J. Birgeneau, B. Keimer, Phys. Rev. Lett. 2013, 111, 017204.

[76] S. P. Bayrakci, B. Keimer, D. A. Tennant, arxiv1302.6476, 2013.

[77] K. F. Tseng, T. Keller, A. C. Walters, R. J. Birgeneau, B. Keimer, Phys. Rev. B 2016, 94, 014424.

[78] B. Fauseweh, F. Groitl, T. Keller, K. Rolfs, D. A. Tennant, K. Habicht, G. S. Uhrig, Phys. Rev. B 2016, 94, 180404.

[79] D. A. Tennant, B. Lake, A. J. A. James, F. H. L. Essler, S. Notbohm, H.-J. Mikeska, J. Fielden, P. Kögerler, P. C. Canfield, M. T. F. Telling, Phys. Rev. B 2012, 85, 014402.

[80] F. Groitl, T. Keller, K. Rolfs, D. A. Tennant, K. Habicht, Phys. Rev. B 2016, 93, 134404.

[81] F. Groitl, Ph.D. Thesis, TU Berlin, 2012.

[82] C. Pfeiferer, P. Böni, T. Keller, U. K. Rößler, A. Rosch, Science 2007, 316, 1871.

[83] P. G. Niklowitz, C. Pfeiferer, T. Keller, M. Vojta, Y.-K. Huang, J. A. Mydosh, Phys. Rev. Lett. 2010, 104, 106406.

[84] X. Lu, D. W. Tam, C. Zhang, H. Luo, M. Wang, R. Zhang, L. W. Harriger, T. Keller, B. Keimer, L.-P. Regnault, T. A. Maier, P. Dai, Phys. Rev. B 2014, 90, 024509.

[85] X. Lu, K.-F. Tseng, T. Keller, W. Zhang, D. Hu, Y. Song, H. Man, J. T. Park, H. Luo, S. Li, A. H. Nevidomskyy, P. Dai, Phys. Rev. B 2016, 93, 134519.

[86] W. Wang, Y. Song, C. Cao, K.-F. Tseng, T. Keller, Y. Li, L. W. Harriger, W. Tian, S. Chi, R. Yu, A. H. Nevidomskyy, P. Dai, Nat. Commun. 2018, 9, 3128.

[87] D. S. Inosov, G. Friemel, J. T. Park, A. C. Walters, Y. Texier, Y. Laplace, J. Bobroff, V. Hinkov, D. L. Sun, Y. Liu, R. Khasanov, K. Sedlak, R. Yu, A. H. Nevidomskyy, P. Dai, Phys. Rev. B 2011, 014429.

[88] S. P. Bayrakci, D. A. Tennant, P. Leininger, T. Keller, M. C. R. Gibson, S. D. Wilson, R. J. Birgeneau, B. Keimer, Phys. Rev. Lett. 2013, 111, 017204.

[89] K. Habicht, Habilitationsschrift, Universität Potsdam, 2016.

[90] K. Habicht, T. Keller, Neutron Larmor Diffraction on Ferromagnetic Samples, Unpublished.

[91] B. Náfrádi, T. Keller, F. Hardy, C. Meingast, A. Erb, B. Keimer, Phys. Rev. Lett. 2016, 116, 047001.