J-NSE "PHOENIX"
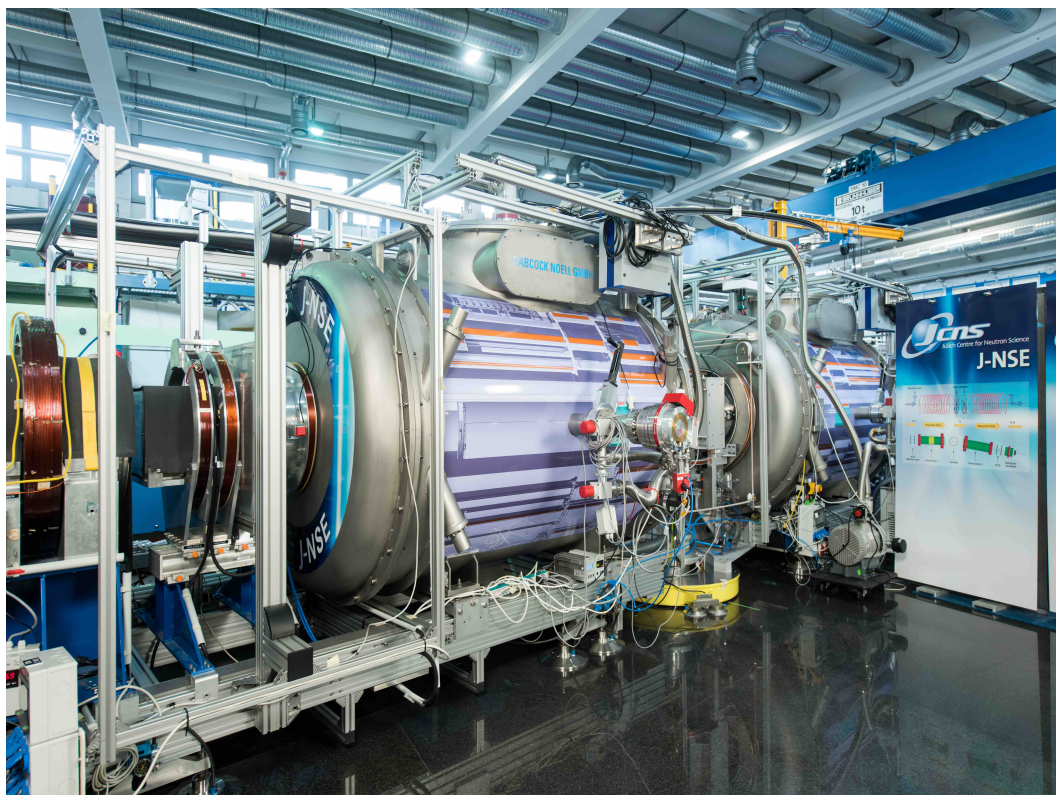
Neutron Spin Echo Spectrometer

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Contents

1 Introduction

Neutron spin echo spectroscopy provides the highest energy resolution in neutron scattering. The covered energy range (or Fourier time range) matches excellently thermally driven motions in soft matter systems such as polymer chains in solution, in the melt, domain motions of proteins, phospholipid membrane fluctuations to mention just a few. This experiment aims to study the dynamics of a polymer chain in solution. Poly(ethylene propylene) (PEP) with a molecular weight of 100 kg/mol is dissolved in deuterated decane with a concentration of 3%. The dynamics of PEP polymer in solution will be studied at room temperature. The results will be interpreted in terms of the Zimm model, which allows to draw conclusions about the internal motions of the polymer chains.

2 Neutron Spin Echo Spectroscopy

The neutron spin echo technique uses the neutron spin as an indicator of the individual velocity change the neutron suffered when scattered by the sample. Due to this trick NSE accepts a broad wavelength band and at the same time is sensitive to the velocity changes down to 10^{-5}. However, the information carried by the spins can only be retrieved modulo an integer number of spin precessions and thus it is retrieved as intensity modulation proportional to the cosine of a precession angle difference. *The measured signal is the cosine transform $I(Q,t)$ of the scattering function $S(Q,\omega)$.* All spin manipulations only serve to establish this special type of velocity analysis. For details see Reference [1].

Due to the intrinsic Fourier transform property of the NSE instrument it is especially suited for the investigation of relaxation-type motions, which contribute at least several percent to the entire scattering intensity at the momentum transfer of interest. The Fourier transform property yields the desired relaxation function directly without numerical transformation and tedious resolution deconvolution. The resolution of the NSE may be corrected by a simple division.

The NSE instrument (see Figure 1) consists mainly of two large solenoids that generate the magnetic field that causes the precession of neutron spin (precession field). The precession of the spin is limited by $\pi/2$-flippers, which are in front of the entrance and respectively exit of the first and second main solenoids; the π-flipper is located near the sample position. The embedding fields for the flippers are generated by Helmholtz-type coil pairs around the flipper locations. After leaving the last flipper the neutrons enter an analyzer containing 60 (30 x 30 cm^2) magnetized CoTi supermirrors located in a solenoid set. These mirrors reflect only neutrons of one spin direction into the multidetector. Figure 1 (middle) shows the layout of the solenoids, the bottom part the engineering design of the J-NSE spectrometer. The main precession coils providing the strong precession region, are superconducting and fully compensated (no dipolar stray fields) in order to minimize the mutual influence of the different spectrometer components.

Depending on its velocity, each neutron undergoes a number of precessions in the first solenoid before hitting the sample. After the scattering process the π-flipper inverts the spin orientation so that the rotation in the second solenoid exactly compensates the first if the speed of the neutrons is not changed by the scattering (purely elastic process), whereas inelasti-

cally scattered neutrons collect a different phase angle of rotation, $\Delta\Psi \simeq \Delta v/v^2\,\gamma\,J$, with $\gamma = 2\pi \times 2913.06598 \times 10^4\,\mathrm{s}^{-1}\,\mathrm{T}^{-1}$ and J being the magnetic field integral (the integrated magnetic field a neutron experiences during its flight through the field). The distribution of the velocity changes Δv of neutrons that experienced an energy transfer during scattering at the sample – in terms of its cos-Fourier transform – is measured as polarization of the neutron beam at the end of the second solenoid after the last $\pi/2$-flipper. *Small velocity changes are proportional to the small energy changes* $\hbar\omega$, ω *being the frequency of the Fourier transform.* The time parameter (Fourier time) is proportional to $\lambda^3 J$ and here in first instance is controlled by the current setting of the main coils, which determins the field integral J.
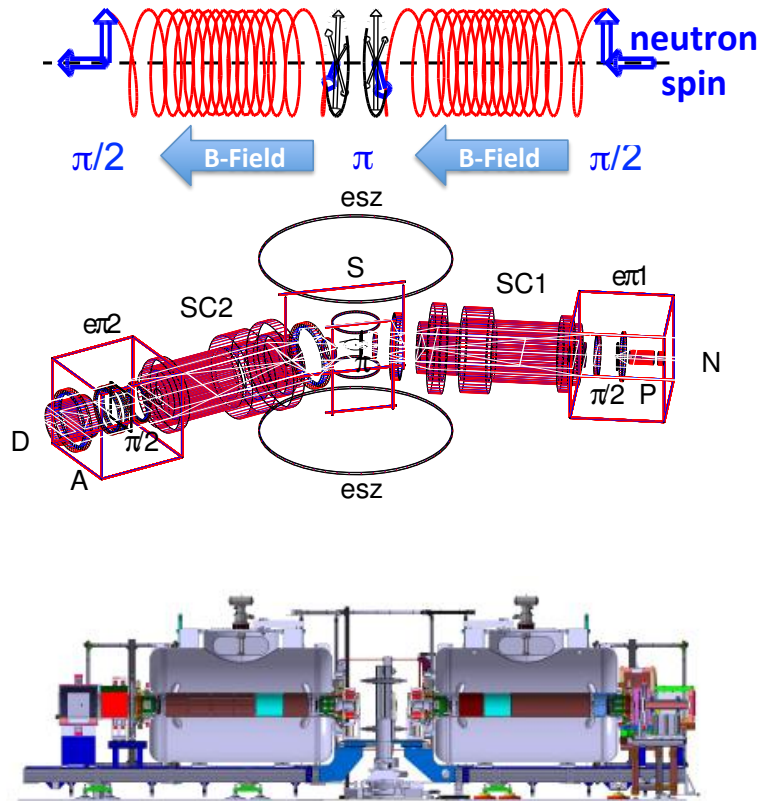

Fig. 1: Working principle of the NSE spectrometer showing the spin precessions along the flight path for the velocity encoding/decoding (top), the magnetic layout of the actual J-NSE spectrometer with all solenoids (middle) and the engineering design of the actual J-NSE spectrometer (bottom) [2, 3].

The polarization is determined by scanning the magnetic field in one of the main coils with the so-called phase coil. If first and second arm are symmetric, a maximum of the polarization is measured. However, if the phase of the spins is shifted by 180 degree by variation of the field of one coil, one gets to a minimum of intensity. With a 360 degree variation one gets to the next maximum and so on. These oscillations are shown in Figure 2. The amplitude of such an echo is normalized to the difference between maximum intensity (up-value), where all flippers are switched off, and the minimum intensity where only the π-flipper is switched on (down-value). Assuming that this normalization accounts for all imperfections of the polarization analysis in the instrument, the result yields the desired degree of polarization reduction due to

inelastic/quasielastic scattering of the sample. Since the thus determined polarization reduction also contains the effects due to field integral inhomogeneity a further normalization step is needed, which is equivalent to a resolution deconvolution in a spectroscopic instrument as e.g. the backscattering spectrometer. In order to be able to perform this resolution correction the same experimental and data treatment procedure has to be carried out with an elastic scatterer.
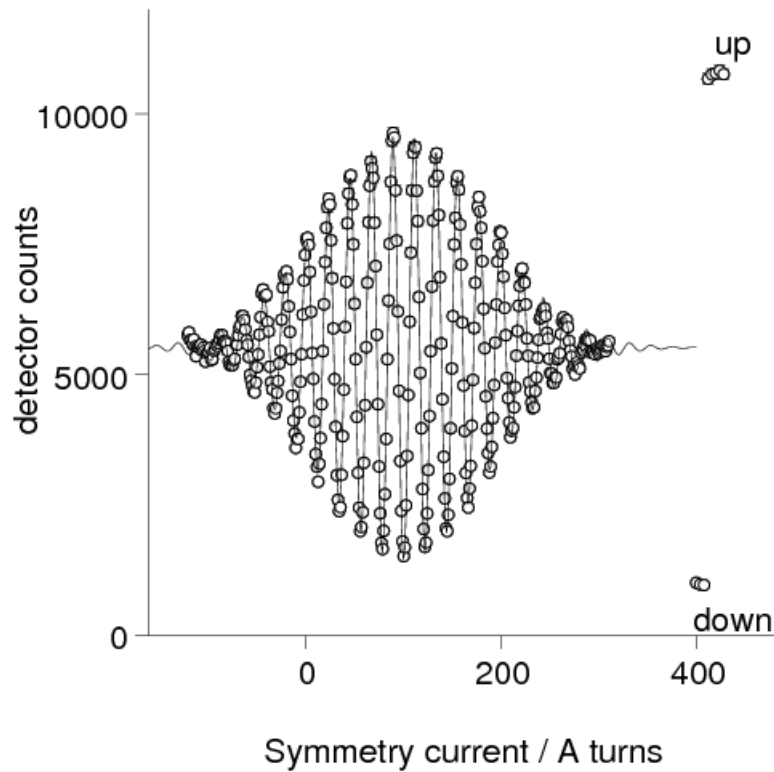

Fig. 2: Echo group measured with the NSE instrument.

For a given wavelength the Fourier time range is limited to the short times (about 3 ps for J-NSE instrument @ MLZ) by the lower limit of the field integral and to long times by the maximum achievable field integral $J = \int Bdl$. The lower limit results from the lowest field values that are needed as "guide" field in order to prevent neutrons from depolarization effects. The upper limit results either from the maximum field that can be produced by the main solenoid, or by the maximum field integral inhomogeniety ($\rightarrow$ variation of precession angle between different paths within the neutron beam) that can be tolerated respectively corrected for, depending which condition applies first. The J-NSE may achieve a $J = 1$ Tm corresponding to $t = 96$ ns at $\lambda = 8$ Å.

The scattering vector Q is determined by the angle 2θ of the second arm of the spectrometer with respect to the first one by $Q = 4\pi/\lambda \sin(\theta)$ (Bragg equation). The Fourier time t is proportional to the magnetic field of the main solenoids. At a given scattering vector Q, the magnetic field is successively increased and an echo group is recorded for each setting to obtain $I(Q,t)$ as a function of t.

2.1   Separation of coherent and incoherent scattering

By the use of polarized neutrons it is possible to separate the coherent and spin incoherent part of the scattering, since the incoherent scattering changes the polarisation to $-1/3$. For different scattering vectors Q the scattering intensity is measured, once in the spin-up configuration and once in the spin-down setup. In the spin-up configuration all spin flippers are switched off and the longitudinal, in forward direction (i.e. parallel to the magnetic field) polarized beam can pass through the spectrometer. The analyzer in front of the detector transmits those polarized neutrons. The measured intensity at the detector in this configuration is the maximum possible intensity. In the spin-down configuration only the π flipper at the sample position is switched on, which rotates the neutron spin orientation by $180°$. The spin direction is now against the magnetic field direction and in the ideal case the analyzer completely absorbs the neutrons, so that the minimal possible detector intensity is measured. Omitting background effects and assuming perfect flipping ratio (ratio spin-up/spin-down = ∞ in the direct beam) coherent and incoherent scattering contributions can be separated as follow (with Up: detector intensity in the diffraction run with all flippers off, $Down$: detector intensity in the diffraction run with only π flipper at sample position on, I_{coh}: coherent scattered intensity, I_{inc}: incoherent scattered intensity):

$$Up + Down = I_{coh} + I_{inc} \tag{1}$$

$$Up - Down = I_{coh} - 1/3 I_{inc} \tag{2}$$

which gives

$$Up = I_{coh} + 1/3 I_{inc} \tag{3}$$

$$Down = 2/3 I_{inc} \tag{4}$$

respectively

$$I_{inc} = 3/2 Down \tag{5}$$

$$I_{coh} = Up - 1/2 Down \tag{6}$$

To include non-ideal flipping ratio and background count rate the calculation is more difficult.

3   Polymer dynamics

There are different models to describe the dynamics of large molecules. A nice overview is given in the book "Neutron Spin Echo in Polymer Systems", which is also available online [4], as well as in laboratory course lectures, chapter 13.

The conformation of a linear polymer chain follows a random walk, this means a chain segment of length l can move freely around the neighboring segment (within the limitation of chemical

bonds). With a set of segment vectors $\mathbf{r}_n = \mathbf{R}_n - \mathbf{R}_{n-1}$, where $\mathbf{R}_n$ is the position vector of segment n, the distance between segments, which are n steps apart, follows a Gaussian distribution [4]:

$$\Phi(R, n) = \left(\frac{3}{2\pi n l^2}\right)^{3/2} \exp\left(-\frac{3R^2}{2nl^2}\right) \tag{7}$$

with l the segment length.

By summing up the scattering amplitudes of the centres of the segments of a polymer chain with the correct phases, one obtains the scattering function of the polymer chain (see Lecture on Dynamics of Macromolecules for more details):

$$I(Q, t) = \langle \sum_{n,m=1}^{N} \exp[i\mathbf{Q} \cdot (\mathbf{R}_n(t) - \mathbf{R}_m(t))]\rangle \tag{8}$$

A snapshot of the chain, i.e. the static structure factor, is obtained for $t = 0$. One gets the well known Debye funktion:

$$I(Q) = N f_{Debye}(Q^2 R_g^2) \tag{9}$$

$$f_{Debye}(x) = \frac{2}{x^2}(e^{-x} - 1 + x) \tag{10}$$

with R_g the radius of gyration of the chain.

3.1 Rouse dynamics

In the Rouse model the Gausssian polymer chain is described as beads connected by springs. The springs correspond to the entropic forces between the beads and the distance between the beads corresponds to the segment length of the polymer. The polymer chain is in a heat bath. The Rouse model describes the movement of the single chain segments of such a polymer chain as Brownian movement. Thermally activated fluctuations (by the stochastic force $\mathbf{f}_n(t)$ with $< \mathbf{f}_n(t) >= 0$), friction force (with friction coefficient ζ) and the entropic force determine the relaxation of polymer chains.

The movement of the chain segments is described by a Langevin equation:

$$\zeta \frac{d\mathbf{R}_n}{dt} + \frac{\partial U}{\partial \mathbf{R}_n} = \mathbf{f}_n(t) \tag{11}$$

The Langevin equation can be solved and one can calculate with equation 8 the intermediate scattering function, which is measured by NSE (for details, see the lecture on "Dynamics of Macromolecules"):

$$I(Q, t) = \exp(-Q^2 D t) I_{intern}(Q, t) \tag{12}$$

with a diffusive part with a relaxation rate proportional to Q^2 and the part describing the internal relaxation, which can be written for $QR_G >> 1$:

$$I_{intern}(Q, t) = \frac{12}{Q^2 l^2} \int_0^\infty du \exp(-u - \sqrt{(\Gamma_Q t)} h(u/\sqrt{(\Gamma_Q t)})) \tag{13}$$
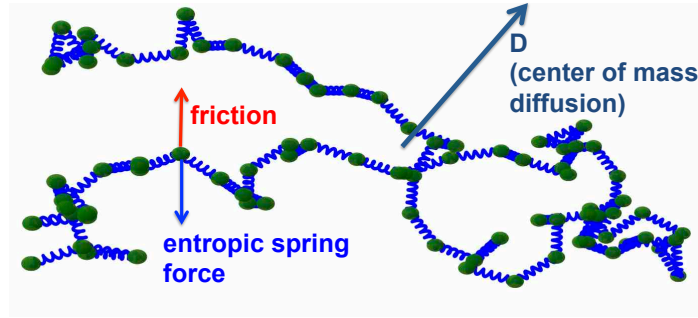
Fig. 3: Schematic representation of the polymer chain in the Rouse model [4] as a Gaussian chain with beads connected by springs.

with the relaxation rate

$$\Gamma_Q = \frac{k_B T}{12\zeta} Q^4 l^2 \tag{14}$$

and

$$h(u) = \frac{2}{\pi} \int dx \cos(xu)(1 - e^{-x^2})/x^2 \tag{15}$$

Note that the local relaxation rate depends on Q^4. When $I(Q,t)/I(Q,0)$ is plotted against the Rouse variable $\sqrt{\Gamma_Q t}$, all curves collapse onto a master curve if the Rouse model holds.

With this model, for example, the dynamics of short polymer chains in the melt can be described. With increasing molecular weight some other effects like the constraints imposed by mutual entanglements of the polymer chains become important, which are described in the reptation model by de Gennes (Nobel prize 1991). In this experiment polymers in solution, not in the melt, are considered. The Rouse model then needs to be extended by hydrodynamic interactions as will be described in the following section.

3.2 Zimm dynamics

Polymers in solution can be described by the Zimm model, where hydrodynamic interaction between the chain segments mediated by the solvent are dominant. Moving chain segments exert forces on other segments due to the flow of the surrounding solvent. Within some approximations the system can be described by a Langevin equation analogous to that of the Rouse model which includes the friction coefficient $\xi = 6\pi\eta a_{seg}$ with η the viscosity of the solvent. The main modification is the inclusion of the hydrodynamic interaction represented by an Oseen tensor to account for the forces acting to neighbouring beads via the flow field of the solvent. More details can be found in Reference [4].

The intermediate scattering function can be written again in the form of Equation 12, with a global diffusion of the whole particle, and the internal polymer fluctuations $I_{intern}(Q,t)$. An approximation to $I_{intern}(Q,t)$ of the Zimm model is a stretched exponential function which reads

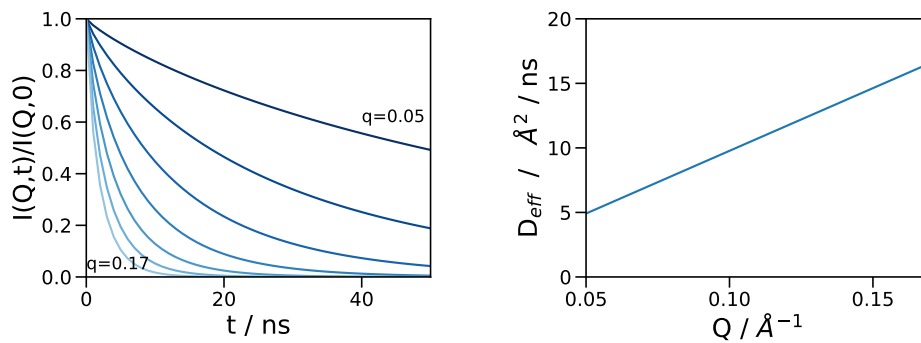$$I_{intern}(Q,t) = \exp\left(-\left(\frac{k_B T Q^3 t}{6\pi\eta b}\right)^\beta\right) \tag{16}$$

Fig. 4: Calculated I(Q,t) with the Zimm model (left) and resulting effective diffusion (Γ/Q^2).

with $b \simeq 1.354$ and $\beta \simeq 0.85$. The relaxation rate of a polymer chain in this model, $\Gamma = k_B T Q^3/(6\pi\eta)$, is mainly determined by the viscosity of the solvent. Internal dynamics is dominant at higher scattering vectors Q, where also the typical Q^3 dependence of the relaxation rate can be observed. At smaller scattering vectors the contribution from the center of mass diffusion is more prominent so that rather a Q^2 dependence of the relaxation rate is expected.

Figure 3.2 shows the calculated I(Q,t) for a series of Q-values (i.e. scattering angles instrument) which will be measured in the labcourse with the NSE spectrometer, together with the resulting relaxation rate divided by Q^2. This should be constant for simple diffusing processes. The linear increase indicates the Q^3-depencence which is characteristic for Zimm dynamcis.

3.3   Center of mass diffusion

With NSE spectroscopy the movements on length scales in the order of nanometer and time scales in the order of nanoseconds can be observed. This matches e.g. the center of mass diffusion of macromolecules in solution or micelles. The mean square displacement of a particle is $< r^2(t) >= 6D_{CM}t$ with the diffusion constant $D_{CM} = k_B T/(6\pi\eta R_G)$, where R_G is the hydrodynamic particle radius and η the viscosity (Stokes-Einstein-relation). The dynamic structure factor which is measured by NSE is then

$$I(Q,t)/I(Q,0) = \exp\left(-1/6 < r^2(t) > Q^2\right) = \exp\left(-D_{CM}Q^2 t\right) \tag{17}$$

This result can be obtained again by the Langevin equation of a particle undergoing Brownian motion in a solvent. A simple diffusion process therefore has a quadratic dependence on the the scattering vector Q.

4   Preparatory exercises

1. How fast do neutrons with a wavelength of 8 Å fly?

2. What is the value of the earth's magnetic field?

3. What is the magnetic field at the surface of a common permanent magnet?

4. How many mm fall neutrons on their way from the entrance of the spectrometer to the detector (about 7 m) due to gravity?

5. How many precessions does a neutron of $\lambda = 8$ Å perform in the main coils if the Fourier time is set to 20 ns? (Angle $\Psi = \gamma/v \int B dl$).

5 Experiment procedure

5.1 The experiment itself

First, the function of the key components of the neutron spin-echo spectrometer will be explained and demonstrated.

The generation of the "Spin Echo" will be demonstrated with an auxiliary phase coil, wound around one of the main precession coils with a simple wire. With a laboratory DC-powersupply connected to this coil, the magnetic field inside this main coil is slightly varied. A fully symmetrical setup with identical magnetic path integrals in both main coils results in a maximum count rate at the detector. Increasing the current in the auxiliary coil from this point results in an additional phase shift of the neutron spin and thus the intensity varies from the maximum to a minimum and further to the next maximum and so on. In this way, the echo group is scanned.

- The frequency of the oscillation (i.e. the current needed to go from one intensity maximum to the next maximum), depends on the field integral and on the wavelength of the neutrons. Approximating the field integral of a current loop allows thus to determine the wavelength of the neutrons in this experiment. This will be done with the recorded data.

The experimental sample under investigation is a polymer chain (PEP, polyethylenepropylene) with a molecular weight of 100 kg/mol in solution (deuterated decane). The PEP concentration is 3 wt %. The first experiment with the sample is to measure the elastic scattering by recording the spin-up and spin-down intensity at the detector.

- The coherent and incoherent scattering of the sample shall be extracted from this reading and plotted versus the scattering vector Q.

The dynamics of the sample is measured. For some selected scattering vectors Q, a series of Fourier times is measured for the sample, for a background sample containing everything but the objects under investigation, in this case the pure deuterated solvent (d-decane), and for an elastic scatterer as reference.

5.2 Data reduction

Each Fourier time is determined by measuring 2-3 oscillations of the echo bunch and fitting the theoretical curve (a cosine oscillation with a gaussian envelope) to the measured points.

In short, the normalized amplitude of the fitted curve is the degree of polarization obtained in this measurement. This elaborated fitting procedure is done with a program called `drspine`, which creates the files containing the intermediate scattering function $I(Q,t)/I(Q,0)$.

5.3 Data evaluation

The $I(Q,t)$ vs. t is contained in the files report_XXXXX.dtr as ascii-data.

- Read in the data with some data treatment program (e.g. free software `qtisas`: https://www.qtisas.com).

- Try to fit the data. First use a simple exponential function $I(Q,t) = A\exp(-\Gamma t)$ and determine the relaxation rate Γ. For diffusion like behaviour with the Stokes-Einstein diffusion coefficient, $\Gamma = DQ^2$ should be valid. Plot Γ/Q^2 vs. Q to check the validity of the model. It also allows for the determiation of the hydrodynamic radius of the particle assuming a viscosity of d-decane of $\eta = 0.954 \times 10^{-3}$ kg/(ms).

- Use a stretched exponential function as model function: $I(Q,t) = A\exp(-[\Gamma t]^\beta)$ and determine the relaxation rate Γ and the stretching exponent β. The Zimm model would predict that the rate depends on the viscosity η as $\Gamma = k_BT/(6\pi\eta)Q^3$. What is the viscosity of d-decane? Does the Q-dependence of the model describes that of the data correctly (i.e. is $\Gamma/Q^3 = const.$)?

6 Experiment related exercises

Data evaluation (the bullet points in section 5):

1. Separate coherent and incoherent scattering from the elastic scan (diffrun) and plot it.

2. Evaluate the data containing $I(Q,t)/I(Q,0)$ vs t with the models as described in the previous section and discuss the results.

General questions:

1. Why are no iron yoke magnets used in the construction of a NSE spectrometer?

2. What is the maximum field inside the main precession coils of the J-NSE?

3. What determines the resolution of the spin echo spectrometer?

4. How does the signal look like if the scattering is spin-incoherent? (Hint: in this case 2/3 of all neutron spins get flipped in the scattering process.)

5. What is the measured effect of the spin echo spectrometer?

6. What is measured finally?

7 J-NSE Training environment

Data reduction and evaluation of the NSE labcourse experiment can be done in the training environment at `https://training.mlz-garching.de/jcns/` where the j-nse relevant data and evaluation software is available in a linux container running in the browser.

The following section describes the basics of the j-nse data structure, data reduction and evaluation and serves as a guideline for the practical part of the labcourse.

7.1 Log into the labcourse training environment

Training environment: http://training.mlz-garching.de/jcns/ User name: will be given during labcourse pwd: will be given during labcourse

1) open terminal emulator (top: Applications -> terminal emulator)

2) `cd` brings you to home directory

3) `cd data` brings you to the directory with the labcourse data

4) `jupyter lab` starts jupyter lab in a web browser.

5) Start the two notebooks `DrSpineMacroGenerator.ipynb` and `pep100_labtest.ipynb`

6) Inside the notebooks: execute the cells with code with shift-ENTER

The notebooks and data reduction tools available here and described in more detail below can be used to get a deeper insight into the working principle of neutron spin echo spectroscopy and in the workflow of data reduction.

7.2 Look at the raw data

In the file browser of the jupyter lab on the left, you can click on the different files and view them in a jupyter sub-tab.

Look at

- `m20104.echo`: raw ascii data of a scan: a single scattering vector q, multiple Fourier times t (=B-Field-setting), at each Fourier time t a scan of the phase coil to record the echo. At each point of the phase coil scan, a detector image (32x32 pixels = 1024 pixels).

- `m20104_ActC4mmQ0.10t0.989ns.dat`: extract of one Fourier time for quick plotting. First column: current in phase coil, then anode signal (detector sum), different sensors (B, Temp) and detector areas.

- `mxx.echo.directory`: Short description of all scans at the instrument (here, extract of the full mxx.echo.directory file). "Electronic labbook".

- `diffract.run`: diffraction only, with 'spin up' (column 7) and 'spin down' (column 12) configuation as a function of q (second column). Can serve as polarized diffraction to extract coherent and incoherent intensity (*one labcourse task, see above*). Mainly for assessing the required measurement time.

7.3 Data reduction: From Detector Images to I(Q,t)

1) Prepare macro for drspine data reduction programm:

  - go to `DrSpineMacroGenerator.ipynb` tab in jupyter lab. Select refs, sample, bgr according to the entries in the mxx.echo.directory (refs: 19968-70, sample 19971-73, bgr 19974-76).
  - "Create macro"
  - possibly execute it right away within the script, BUT: more insight with separate execution
  - if you execute it, also execute the two cells at the end with the pdflatex and the qpdfview command to get the pdf report.

2) open another Terminal, `cd`, `cd data`, then call `$HOME/local/bin/drspine` and within the program then the created macro `macname1` (or the name you gave). Already prepared macro: `drpep` in case the macro generation fails.

3) A pdf with the report of the evaluation opens with details concerning the fits, but also some "standard evaluation" of the intermediate scattering function I(q,t).

If the pdf report does not open (for the macro generator this is the case) call `pdflatex report19971_1.tex` followed by `qpdfview-qt5 report19971_1.pdf` in the terminal window or directly in drspine. -BUT BEFORE: Study the details below:

7.3.1 Details of data reduction

First check: required python environment installation? Call

`sh $HOME/local/bin/drspine_create_env.sh` and
`source $HOME/local/bin/drspine_activate.sh`
in a Terminal window.

These two commands are in `cd`, `cd drspine`, `tail -15 INSTALL.md`

(If you changed to the drspine directory, don't forget to navigate back to the data directory with `cd`, `cd data`)

With
`alias drspine='$HOME/local/bin/drspine'`
starting drspine gets a bit easier (just `drspine` instead of the path.

Details which can be studied: with the drspine program: call
```
dump
```
to save all fitting details.

Echo fits across the 2D detector, e.g. for the reference:
```
drspine --> plot fits run 19969 tau 1
```
(then the python command line opens, from there, the same things can be called with:)

```
plot_fits('./fits_19969',tau=1,npix=8,)
```

> Troubleshooting in case the fits do not work: Reinstall the ipython environment
> with the following commands:
> ```
> cd, cd .ipython rm -rf profile_drspine/
> ```
> Then reinstall the profile with
> ```
> sh $HOME/local/bin/drspine_create_env.sh
> source $HOME/local/bin/drspine_activate.sh
> ```
> see above. Then it should work.

High fourier time (good echos throughout the detector, since it is an elastic scatterer, with some
reduction in polarization due to imperfections of the instrument):

```
drspine/plot [2]: plot_fits('./fits_19969',tau=10,npix=8,)
```

PEP polymer in deuterated decane, low fourier time (good echos throughout the detector):

```
drspine/plot [2]: plot_fits('./fits_19972',tau=1,npix=8,)
```

Hig fourier time: (already fainted echos throughout the detector due to the decay in I(q,t)):

```
drspine/plot [2]: plot_fits('./fits_19972',tau=10,npix=8,)
```

Deuterated decane, low fourier time: Already almost no echco, dynamics so fast that everything
already decayed; much weaker intensity:

```
drspine/plot [2]: plot_fits('./fits_19975',tau=1,npix=8,)
```

Close python command line with ctrl-d, quit drspine with `quit`.

create pdf report (if not done automatically): 1) pdflatex report...tex 2) qpdfview-qt5 report...pdf

7.4   Final data: I(q,t)

Ascii results of I(q,t) vs t for different sets of q are in the .dtr files and also in last_sqt.dat. The pdf report contains a tentative "standard" analysis. Further analysis can then be done by fitting the datasets with some model, e.g. with jupyter notebooks, origin, qtisas (a free origin clone adapted to scattering).

Follow data evaluation suggestions from section .

7.5   Data evaluation and fitting example

The notebook `pep100_labtest.ipynb` gives an example of some fits with different models to the data.

Note: if there are remaining calls to dpd (commands starting with dpd.xxx), just delete "dpd." and re-execute the cell.

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[3] S. Pasini, O. Holderer, T. Kozielewski, D. Richter, M. Monkenbusch, *J-NSE-Phoenix, a neutron spin-echo spectrometer with optimized superconducting precession coils at the MLZ in Garching*, Review of Scientific Instruments **90**, doi:10.1063/1.5084303 (2019).

[4] D. Richter, M. Monkenbusch, A. Arbe, J. Colmenero, *Neutron spin echo in polymer systems*, in *Neutron Spin Echo in Polymer Systems*, pp. 1–221 (Springer, 2005).

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