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A compact neutron Ramsey resonance apparatus for polarised neutron radiography

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ABSTRACT

A compact apparatus to perform polarised neutron radiography on macroscopic objects is presented. Its working principle, based on Ramsey's resonance technique, allows to observe interactions between neutron spins and magnetic fields. Despite its shortness of only 480 mm, the magnetic field homogeneity allows for large beam cross-sections of up to $20 \times 20\,\text{mm}^2$. The applied magnetic field at the sample position is variable and can be tuned from about 4 to almost 32 mT without violating the Ramsey resonance condition. The performance of the apparatus is demonstrated in systematic tests, which show a phase stability of 1 degree and a sensitivity of about 7.5×10^{-8} Tm.

1. Introduction

Ramsey's technique of separated oscillating fields is a method sensitive to spin-dependent interactions of particles with external fields, detected as a spin precession angle φ [1,2]. This technique adapted to neutrons can be employed to observe interactions between neutron spins and magnetic or pseudomagnetic fields, i.e. spin-dependent interaction with polarised nuclei [3–5].

A neutron Ramsey apparatus[1] consists ideally of a homogeneous steady magnetic field $\boldsymbol{B}_0$ where the spins of a well-collimated and monochromatic polarised neutron beam get non-adiabatically flipped twice by 90° by two superimposed phase-locked fields oscillating perpendicularly to $\boldsymbol{B}_0$ with the angular frequency ω ($\pi/2$-*spin flippers*). Between the spin-flips the neutron spins precess freely in the plane perpendicular to the steady field and get analysed by a neutron spin filter behind the second $\pi/2$-spin flipper. To ensure that the neutron spins precess on average in phase with the oscillating fields the so-called *Ramsey resonance condition* must be fulfilled, saying that the average steady magnetic field along the neutron flight path between the $\pi/2$-spin flippers must be equal to the field at the position of the oscillating fields. This implies that the steady magnetic field does not necessarily need to be homogeneous. Successive scanning of the angular frequency ω close to the neutron Larmor frequency $\omega_0 = -\gamma_n \boldsymbol{B}_0$, where γ_n is the gyromagnetic ratio of the neutron, results in a sinusoidal intensity oscillation (*Ramsey pattern*). Any additional precession angle φ of the neutron spins between the $\pi/2$-spin flippers can be measured as an equally sized phase shift of the Ramsey pattern modulo 360°.

As originally proposed in Ref. [7] the combination of a Ramsey apparatus with a standard neutron radiography setup makes it possible to take two-dimensional images of magnetic and pseudomagnetic fields, e.g. produced by ferromagnetic materials or samples containing polarised nuclear spins (*neutron spin phase imaging*). The here presented compact Ramsey apparatus was designed to further explore the possibilities of this novel method.

2. The Ramsey apparatus

A scheme of the 480 mm long Ramsey apparatus is presented in Figs. 1 and 2. The setup consists of two 4 mm-thick ferromagnetic steel plates (a), which are connected at every corner by four blocks, each assembled from two NdFeB/N35 permanent magnets[2] (b) and a sandwiched ferromagnetic steel block (c). Each steel block is wound with a coil of 3×50 windings of 0.7 mm diameter copper wire, which can be used to trim the magnetic field produced by the permanent magnets. This yields a mean magnetic field of about 18 mT, corresponding to a neutron Larmor frequency of about 530 kHz, in the centre of the $100 \times 480 \times 65\,\text{mm}^3$ volume. The magnetic field strength in z-direction along the neutron flight path has been measured and is plotted in Fig. 3. It shows a plateau of $B_0 = (17.94 \pm 0.04)$ mT from $y = 180$ to 300 mm, where the neutron spin precession takes place. Due to the trimming, the field at both ends of the apparatus

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[1] A theoretical description of a Ramsey apparatus can be found in Ref. [5,6].

[2] www.maurermagnetic.ch.

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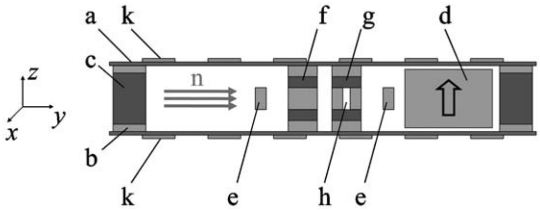

Fig. 1. Scheme of the Ramsey apparatus with the monochromatic polarised neutron beam (n) coming from the left. (a) ferromagnetic steel plates ($100 \times 480 \times 4\,mm^3$), (b) permanent magnet blocks ($15 \times 40 \times 8\,mm^3$), (c) ferromagnetic steel blocks ($12 \times 40 \times 49\,mm^3$) wound with copper wire serving as trim coils, (d) neutron polarisation analyser, (e) radio frequency $\pi/2$-spin flippers, (f) split pair coil (compensation coil), (g) split pair coil (sample coil), (h) $4 \times 20\,mm^2$ slit for sample positioning and (k) copper tubes with cooling water soldered on copper plates, which are thermally anchored to the steel plates. Drawing is not to scale.

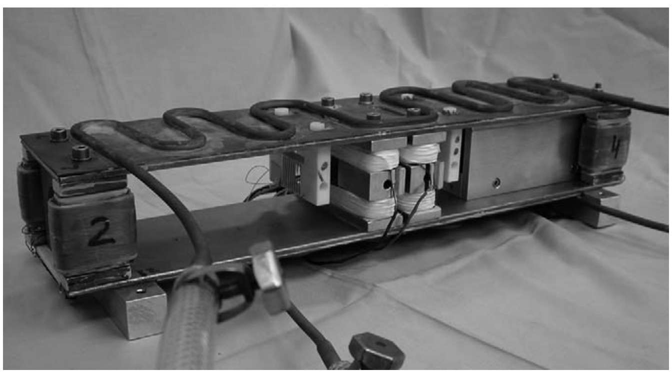

Fig. 2. Photograph of the Ramsey apparatus.

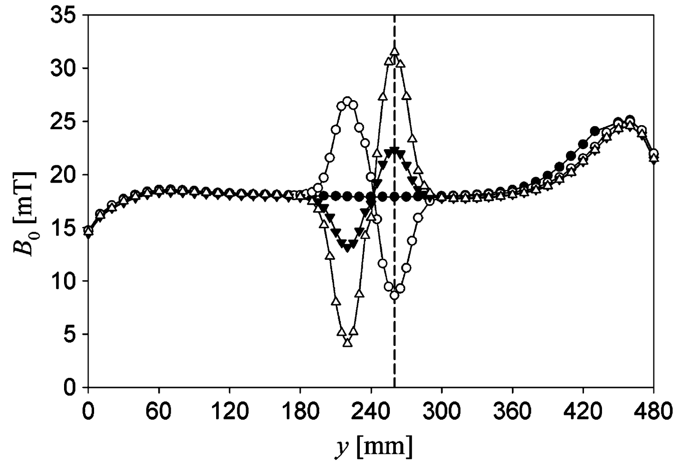

Fig. 3. Plot of the magnetic field strength in z-direction along the neutron flight path in the centre of the volume enclosed by the steel plates. The field was determined for different currents in the sample coil and the compensation coil: $I_s = I_c = 0\,A$ (filled circles), $I_s = -I_c = -2\,A$ (white circles), $I_s = -I_c = +1\,A$ (filled triangles) and $I_s = -I_c = +3\,A$ (white triangles). The vertical dashed line at $y = 260\,mm$ marks the sample site. The two 10 mm-thick $\pi/2$-spin flippers can be freely positioned at $y = 180$–$190\,mm$ and $y = 290$–$300\,mm$, respectively. For the measurement a vector field probe connected to a *LakeShore* 460 3-channel gaussmeter was used. The magnetic field was scanned in steps of 10 mm.

diverges from the field in the plateau region. But this does not harm the functionality of the Ramsey apparatus, as there the field only serves as a holding field for the neutron polarisation and the magnetisation of the remanent transmission spin analysing device[3] (d), respectively.

The two radio frequency $\pi/2$-spin flippers (e) are $24 \times 10 \times 23\,mm^3$ box-shaped coils, which are wound on a Teflon body with a $20 \times 20\,mm^2$ window for neutrons. Each coil consists of 9 turns of a 0.3 mm diameter bare copper wire with a pitch of 3 mm and produces a linear oscillating field along the x-axis. They are connected in series and form the inductance of a matched resonant circuit for frequencies around 790 kHz. The circuit is driven far off resonance by a signal generator and a 250 W power amplifier at about 550 kHz to profit from the almost flat power absorption spectra of the circuit in the operating frequency range.[4] The distance between the $\pi/2$-spin flippers can be adjusted between 100 and 120 mm to optimise for the Ramsey resonance condition.

To apply magnetic fields on a sample, which differ from the field provided by the permanent magnets, it is necessary to compensate the additional field integral along the neutron flight path by a compensation coil to fulfill the Ramsey condition. The compensation coil (f) and the sample coil (g) are two identical rectangular split pair coils consisting each of 2×150 windings of 0.7 mm diameter copper wire wound on an aluminium body. The cross-sections of the windings have a size of $15 \times 7.5\,mm^2$ and are vertically separated by a 20 mm distance, which allows for a $20 \times 20\,mm^2$ neutron beam window. Each coil produces a magnetic field with a strength[5] of about 4.4 mT/A along the z-axis. In the following the convention is used, that a positive (negative) current in the coil strengthens (weakens) the steady field produced by the permanent magnets. During the normal operation of the Ramsey apparatus the polarities of the applied voltages are chosen such that the fields are pointing antiparallel to each other, as presented in Fig. 3. Furthermore, the plot shows that the magnetic field at the position of the $\pi/2$-spin flippers stays almost constant, while the sample field can be chosen freely over a large range. Hence, the field at the sample position (h) can be varied from about 4 up to 32 mT. In principle lower or higher fields can be achieved but produce depolarisation at the edges of the neutron beam, as the magnetic field direction inverts due to the stronger field close to the coil windings. On the other hand, a short-time inversion of the magnetic field above the coercivity over the whole sample size can be used to demagnetise ferromagnetic samples.

A picture of the Ramsey apparatus is given in Fig. 2 showing the meandering water cooling tubes (k) soldered on copper plates. They stabilise the temperature of the setup to 20 °C and avoid unwanted phase drifts of the neutron spins and the Ramsey patterns due to thermal expansions.

3. Systematic performance tests

The performance of the Ramsey apparatus has been tested with the cold polarised neutron reflectometer Narziss at the spallation neutron source SINQ at the Paul Scherrer Institute. The monochromator of the reflectometer provides a neutron beam with a wavelength spectrum which peaks at $\lambda_0 = 5\,Å$ and has a width $\Delta\lambda/\lambda_0$ of 1.5%. The beam size is restricted by two cadmium diaphragms in front of the apparatus, with rectangular holes of 1 mm width, 5 mm height and a distance of 725 mm between each

[3] For a detailed description of the device see Ref. [8].

[4] The forward and reflected power of the amplifier are 125 and 113 W, respectively, which yields an absorbed rf-power of about 12 W for both $\pi/2$-spin flippers.

[5] This field strength was measured in the center of the neutron beam window, with the coils placed between the ferromagnetic steel plates.