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Magnetic field devices for neutron spin transport and manipulation in precise neutron spin rotation measurements

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ABSTRACT

The neutron spin is a critical degree of freedom for many precision measurements using low-energy neutrons. Fundamental symmetries and interactions can be studied using polarized neutrons. Parity-violation (PV) in the hadronic weak interaction and the search for exotic forces that depend on the relative spin and velocity, are two questions of fundamental physics that can be studied via the neutron spin rotations that arise from the interaction of polarized cold neutrons and unpolarized matter. The Neutron Spin Rotation (NSR) collaboration developed a neutron polarimeter, capable of determining neutron spin rotations of the order of 10^{-7} rad per meter of traversed material. This paper describes two key components of the NSR apparatus, responsible for the transport and manipulation of the spin of the neutrons before and after the target region, which is surrounded by magnetic shielding and where residual magnetic fields need to be below 100 μG. These magnetic field devices, called input and output coils, provide the magnetic field for adiabatic transport of the neutron spin in the regions outside the magnetic shielding while producing a sharp nonadiabatic transition of the neutron spin when entering/exiting the low-magnetic-field region. In addition, the coils are self contained, forcing the return magnetic flux into a compact region of space to minimize fringe fields outside. The design of the input and output coils is based on the magnetic scalar potential method.

1. Introduction

The determination of very small neutron spin rotations ($d\phi/dz \approx 1 \times 10^{-7}$ rad/m) in the interaction of polarized low-energy neutrons and unpolarized matter is of relevance for different reasons. Corkscrew neutron spin rotations of transversely polarized neutrons can come from the weak interaction between the neutrons and the atoms of the material they interact with. The nucleon-nucleon (NN) weak interaction remains poorly understood due to the dominance in intensity of the strong interaction and the non-perturbative nature at low energies of the theory that describes it, quantum chromodynamics (QCD). The measurement of the weak coupling constants that appear in the theories that aim to describe the interaction and that cannot yet be calculated accurately [1–3] is underway by several experimental collaborations. Experiments that involve few-nucleon systems and low-energy polarized neutrons have been developed to measure PV observables that arise from the NN weak interaction [4–6]. These observables can be related to the weak coupling constants and a lot of effort has been dedicated to determine enough linearly independent combinations of them, in systems where the uncertainties related to nuclear wavefunctions are smaller than in the case of many-nucleon systems [7,8].

A different aspect of neutron spin rotations as a result of the interaction of neutrons with matter is the possibility to search for exotic forces. In particular for the case of forces with relatively long range (μm to cm) that depend on the spin of one (or both) of the interacting particles, experimental constraints are scarce due to the technical challenges that macroscopic amounts of polarized matter impose on precision experiments. However, setting limits on these type of forces is important since a number of theories predict the existence of new interactions mediated by light particles with weak couplings to matter and long ranges, either as a result of broken symmetries in theories beyond the Standard Model, or from theoretical attempts to explain dark matter and dark energy [9–11]. Polarized low-energy neutrons have emerged as an effective tool to search for these type of forces since intense beams of polarized neutrons are available, their momentum transfer corresponds to the mesoscopic scale and, because of their lack of electric charge, they can pass through macroscopic amounts of matter suffering very small attenuations.

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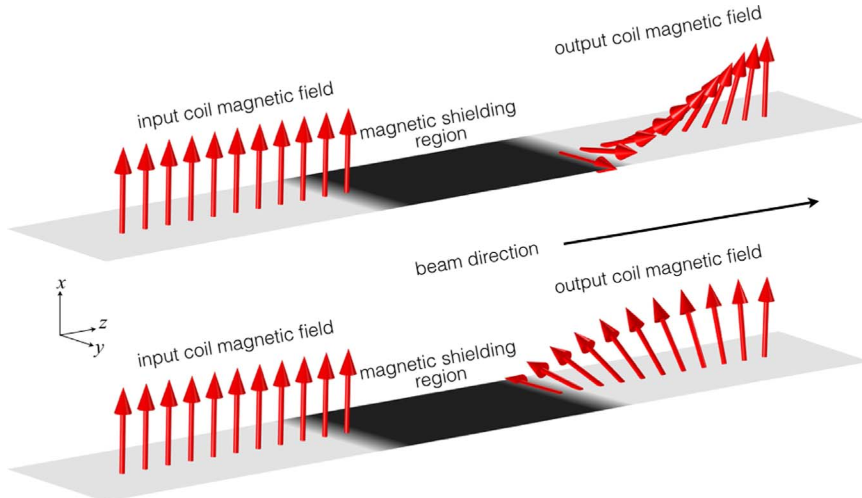

Fig. 1. Scheme of the magnetic fields for neutron spin transport at the entrance and exit of the magnetic shielding region. The top figure illustrates the magnetic field for counterclockwise rotations of the transverse neutron spin component after the magnetic shielding, while the bottom figure illustrates the field for clockwise rotations.

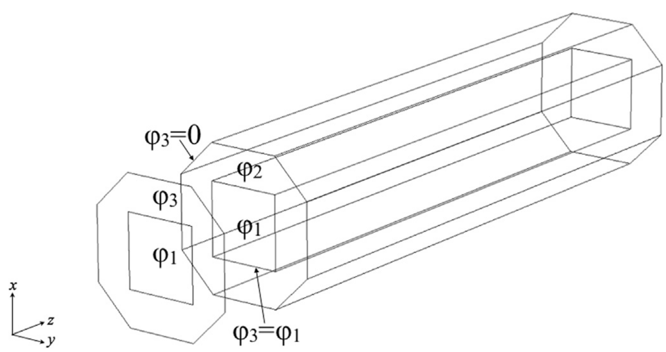

Fig. 2. Geometry of the input and output coils and their endcap. The different magnetic scalar potential regions are marked.

The Neutron Spin Rotation (NSR) collaboration has built a slow neutron polarimeter to measure neutron spin rotations that are of the order of tenths of micro radians per meter of traversed target material. The experimental apparatus, described in detail in [12], has several purposes: It was first developed to measure the PV neutron spin rotation angle for polarized neutrons passing through unpolarized ^{4}He, however it was found that the results of the first stage of this experiment [6] could set the most stringent constraints, in the sub-cm range, for a possible PV exotic force between the neutron and matter, mediated by the exchange of a light spin 1 boson and the first upper bound on parity-odd components of possible in-matter gravitational torsion coupled to neutrons [13]. The upgraded version of the NSR apparatus, to be used to improve the measurement of the PV NSR in n-^{4}He (weak interaction as well as PV exotic forces) is also being used in an experiment to search for a possible parity-even exotic force between neutrons and matter that depends on the neutron spin and velocity and that is mediated by the exchange of spin 1 light bosons (meV mass range) with axial couplings [14]. This paper describes two key pieces in the NSR apparatus: the input and output coils that transport and manipulate the neutron spin before and after the target low-magnetic-field region. In Section 2 we describe the physics of adiabatic and nonadiabatic neutron spin transport as well as the magnetic field requirements for the NSR apparatus. Section 3 describes the technique, based on the magnetic scalar potential, used in the design of the coils. The characterization of the magnetic fields produced by the coils is described in Section 4. Finally, the conclusions are presented in Section 5.

2. Neutron spin transport and magnetic field requirements for the NSR apparatus

Neutrons are fermions with spin $s = \hbar/2$. They also possess a magnetic moment that is antiparallel to the spin ($\vec{\mu} = -\gamma_n \vec{s}$, $\gamma_n = 1.83247172 \times 10^4\ \mathrm{s^{-1}G^{-1}}$). In the presence of an external magnetic field $\vec{B}$, from a semiclassical point of view, a torque is exerted on the neutron spin ($\vec{\tau} = \vec{\mu} \times \vec{B}$), causing it to precess about $\vec{B}$ with a frequency given by $\omega_L = \gamma_n |\vec{B}|$, known as the Larmor frequency. If the external field is homogeneous, the projection of the precession axis of the rotating neutron spin will maintain its orientation relative to the external field. In the case of an inhomogeneous external magnetic field, the relative orientation of the neutron spin projection and the field can be maintained if the fractional rate of change of the field as seen in the rest frame of the neutron ($1/\tau = 1/|\vec{B}|\,|d\vec{B}/dt|$) is small compared to the precession frequency of the neutron spin (ω_L), or in terms of the adiabaticity parameter η:

$$\eta = \frac{1}{|\vec{B}|}\left|\frac{d\vec{B}}{dz}\right|\frac{v_n}{\omega_L} = \frac{1}{B^2}\left|\frac{d\vec{B}}{dz}\right|\frac{v_n}{\gamma_n} \ll 1 \tag{1}$$

with z the direction of propagation of the neutron [15]. On the other hand, if the adiabaticity condition (1) is not met, the neutron spin projection will not maintain its relative orientation with the external magnetic field. The ability to establish both adiabatic and nonadiabatic conditions is important for neutron spin transport.

The NSR apparatus, described in [12], is a neutron polarimeter that is capable of isolating neutron rotary powers that are in the 10^{-7} rad/m range. The magnetic field of the earth as well as other background magnetic fields present in an experiment can produce much larger neutron spin rotations over distances of order a meter than the neutron-matter interactions of interest. For example, a magnetic field of only 0.5 G (the earth's magnetic field ranges between 0.25 and 0.65 G) can produce a rotation by an angle of 90° over a distance of only 5 cm for neutrons with energy of 5 meV (978 m/s of velocity). The determination of very small neutron spin rotations requires, among other things, that the neutron-matter interaction region is surrounded by a magnetic shielding, so that the magnetic fields are below 100 μG. Polarized neutrons, however, need to be transported in and out of this low-magnetic-field region. Entering neutrons require a vertical homogeneous static field to preserve their neutron polarization direction during transport from a super-mirror (SM) neutron polarizer, while exiting neutrons require a static non-homogeneous field to rotate the