令和６年度　９月修了

京都大学大学院理学研究科

ＤＣ３回生研究発表会
要旨集

２０２４年7月９日（火）

物理学第一分野

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場所：理学研究科５号館　５階・第四講義室
発表：２０分（別に質問１０分程度）

２０２４年7月9日（火）９：００～　開始

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Neural Network Quantum States and Quantum Skyrmions

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Abstract We study the ground state properties and time dynamics of quantum skyrmions using neural network quantum states as variational wave functions. We show that the spins in the quantum skyrmion ground states are entangled. We also provide a way to move quantum skyrmions using a magnetic field.

Magnetic skyrmions are topologically protected spin structures with vortex-like configurations, discovered in a variety of materials, including MnSi, FeCoSi, FeGe, and hold potential as denser memory devices and qubits [1]. The size of these quasiparticles can range from micrometers to a few times the atomic lattice spacing, where quantum effects become important. Most research in skyrmions has been done only in the classical regime, and it is not clear if that is applicable to these ‘quantum skyrmions’. Thus, a purely quantum mechanical analysis is needed to study quantum skyrmions. However, the wave function of interacting quantum systems scales exponentially with the system size, which makes its exact calculation impossible for more than a few particles and approximation methods are needed to study systems with large number of particles.

In this research, we study the ground state properties and time dynamics of quantum skyrmions using variational Monte Carlo with artificial neural networks as the trial state. We consider a two-dimensional quantum Heisenberg model with Dzyaloshinskii-Moriya interaction (DMI). First, we show that the ground state accommodates a quantum skyrmion for a large range of Hamiltonian parameters [2]. The spins in these quantum skyrmions are weakly entangled, and the entanglement increases with decreasing DMI. We also find that the central spin is completely disentangled from the rest of the lattice, establishing a non-destructive way of detecting this type of skyrmion by local magnetization measurements. Then, we study the dynamics of quantum skyrmions under an external magnetic field gradient using the time-dependent variational principle [3]. We show that field gradients are an effective way of manipulating and moving quantum skyrmions, which is necessary for realizing their applications. Our research shows that artificial neural networks offer a promising way of studying quantum magnetic systems that are outside the realm of exact diagonalization.

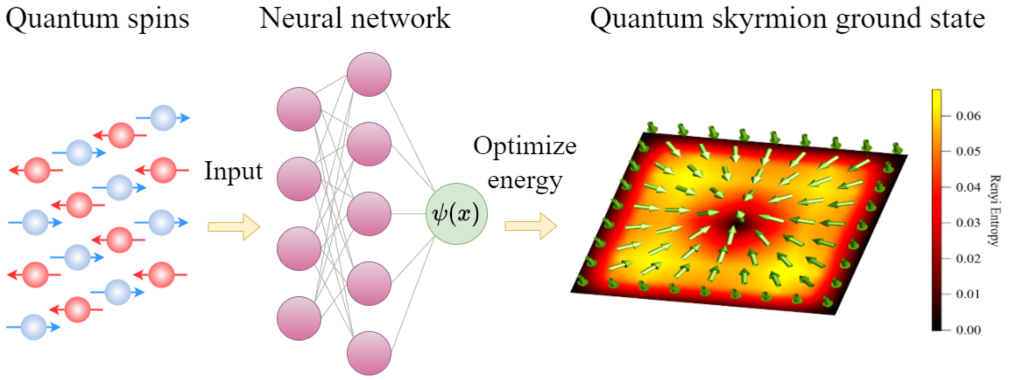

Fig. 1 Representing the quantum skyrmion ground state using an artificial neural network. The input to the network x are quantum spin configurations. The output of the network is the wave function which it learns by minimizing the energy. The spins in the quantum skyrmion are entangled as shown by the heatmap plotting the Renyi entropy.

References

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Coherent spin switching driven by THz-magnetic-field-modified potential energy

Optical Materials Science Group　　Zhenya Zhang

Abstract We studied the coherent control of magnetization in the canted antiferromagnet $Sm_{0.7}Er_{0.3}FeO_3$. We observed spin switching after the first half cycle of the quasi-ferromagnetic mode and found that this phenomenon is driven by the dynamical modification of the potential energy of magnetization induced by the strong multicycle THz magnetic fields.

A good understanding of spin dynamics is essential for the design and development of spintronic devices for information transport, processing, and recording. In contrast to ferromagnets, antiferromagnets have the high-speed spin precession at terahertz (THz) frequencies as a result of the robust antiferromagnetic exchange interaction. Thus, the ultrafast control of antiferromagnetic spins has attracted considerable interest. In previous studies, optical pulses in the range from visible to mid-infrared frequencies have been demonstrated accessible for the coherent spin excitation. However, these methods often lead to significant heating, because the spin excitation in these studies are mediated by the excitation of either electrons or phonons. THz pulses has emerged as an excellent tool for coherent spin excitation that does not involve a strong excitation of electrons or phonons due to the low photon energies. The Zeeman torque applied by the magnetic components of THz pulses can coherently excite the spin dynamics which are available in various antiferromagnets and temperature ranges [1]. However, due to the relatively weak magnetic field of THz pulses propagating in free space, many experiments on nonlinear coherent spin dynamics in antiferromagnets can only investigate a restricted range of phenomena.

In this study, we investigated the coherent spin switching in a canted antiferromagnet $Sm_{0.7}Er_{0.3}FeO_3$ near room temperature using Tesla-class THz magnetic fields. To generate a Tesla-class THz magnetic field in the sample, we designed a spiral-shaped microresonator and fabricated it on the sample surface by electron-beam lithography [2-4]. When the microresonator is irradiated with a THz pulse, an oscillating current is induced that generates a strong multicycle THz magnetic near-field at about 0.46 THz perpendicular to the sample surface. The coherent spin dynamics initiated by the THz magnetic near-field are detected by measuring the change in the ellipticity angle ($\Delta\eta$) of an 800-nm probe pulse due to the magneto-optic effect.

The time-resolved signal $\Delta\eta$ exhibited an oscillation of the quasi-ferromagnetic (q-FM) mode (<0.05 THz). As the field strength is increased beyond a critical value, a long-lived offset emerges after the first half cycle of the q-FM mode, and the amplitude of this offset exhibits a steep dependence on the field strength. The threshold behavior indicates that spin switching occurs after sufficiently strong excitation, that is, the magnetic order parameter overcomes the barrier and reaches the second minimum of a potential energy. We derived and solved the sine-Gordon equation based on the Landau–Lifshitz–Gilbert equation to reproduce the q-FM-mode dynamics and the spin switching. To explain why the offset emerges after the first half q-FM-mode cycle, we analytically solved the sine-Gordon equation by replacing the expression for the potential modified by the fast-oscillating magnetic field with a “time-averaged” effective potential that varies with the envelope of the field. We found that the effective potential initially drives the magnetic order parameter away from the barrier, and when the potential modification vanishes, the magnetic order parameter starts to approach the barrier and overcomes it due to the inertia effect. These results clarify the nonlinearities of the q-FM mode in this antiferromagnet [5].

References

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