Research Experience

Ferromagnetic insulators (FIs) are promising components in non-silicon computing, spanning applications from Boolean logic to wave computing and potentially even quantum computing[1,2]. My research has focused on theoretically studying and manipulating magnons (elementary excitations of FIs) in the quantum domain, a field known as **quantum magnonics**. The long term goal of my research is to contribute towards building quantum applications employing magnons. To this end, I propose the project on **Quantum Transport of Magnons in Ferromagnetic Insulators** that will develop our understanding of microscopic quantum properties of traveling magnons and build foundations for designing magnet-based solid-state quantum communication channels.

Background: This proposal combines techniques from both **magnonics** and **quantum protocols**. My relevant background in these topics is summarised here with details to follow.
Magnonics: I have an extensive experience with hybrid systems involving magnons coupled to *optical photons* in cavities and waveguides, as demonstrated through my papers[3–10]. These works include optimizing magnon-photon coupling, solving coupled magnon-photon dynamics and quantum measurements of magnons using photons. Additionally, I studied magnons coupled with *quantum electrodynamics (QED)* setups that consist of microwaves and superconducting transmons, as shown by my papers[11–15]. These projects involved theoretical modelling and quantum simulations of magnon-QED systems. My research on magnonics included magnon mode calculations using microscopic ferromagnetic models[3,6,8], which is foundational for studying magnon transport.
Quantum Protocols: I have developed protocols for *generating quantum states* of magnons[13,14]. The purpose of these protocols is to design excitation pulses that result in a given magnon state. Further, I developed a protocol for *quantum tomography* of magnon states[9], applying maximum likelihood estimate on photons scattered by magnons. Focusing on a direct application of *quantum transduction* via magnons, I worked on a protocol to create two-qubit gates mediated by magnons[15]. Beyond magnetism, I have worked on a quantum communication protocol with *quantum error correction* in optical fibers[16], which can be adapted to magnon-based communication.

Select Research Works: My PhD research focused on understanding and optimizing optical photons as a quantum interface to magnons. I utilized **optical cavities**, namely whispering gallery mode cavities, made of a ferromagnetic material to enhance magnon-photon coupling[3,4]. Collaborating with *Dr. James Haigh*, an experimentalist at Cambridge, we demonstrated this cavity-enhanced coupling[4]. A key finding of my research was the identification of the magnon modes that have a nearly perfect overlap with optical modes in such cavities[6]. With a high overlap, it becomes feasible to achieve a coupling rate higher than magnon dissipation, a condition required for any optical manipulation of magnons. As applications, I analyzed optically-induced cooling[5] and coherent pumping[7] of high-momentum magnons that are hard to access by commonly used microwave methods.
Post PhD, my interests shifted towards *quantum state generation* in magnons, adapting ideas

from quantum optics and cavity QED to magnonic systems. I proposed a method to generate a superposition of two semi-classical magnetization states, a **spin cat state**, using an anisotropic magnet coupled to a microwave cavity[13]. This proposal was developed in collaboration with *Dr. Alexy D Karenowska*, an experimentalist in quantum magnonics at Oxford. Cat states are interesting for applications as they enable quantum error correction[17].

A given quantum architecture employing magnons will typically require unique initial conditions on magnons. For this purpose, I developed a protocol to generate an **arbitrary quantum state** of the magnons[14], using their coupling to a superconducting transmon as shown in Fig. 1(a). Given a desired magnon state, the protocol involves designing specific pulses to excite the transmon such that the magnon-transmon interaction leads to the magnon's state being the desired one. I evaluated the protocol by a numerical simulation including dissipation and transmon non-idealities, with realistic experimental parameters. Fig. 1(b) shows the results for a cat state and a superposition of fixed magnon (Fock) states, the latter state being the desired initial state for quantum sensing of magnetic fields. A comparison of the Wigner functions, which are quasi-probability distributions, of 'target' and 'achieved' shows that the protocol *maintains the salient features* of each state such as the peak probability locations and the coherence fringes unique to each state. A special case of this protocol was used to experimentally demonstrate a single magnon Fock state[18].

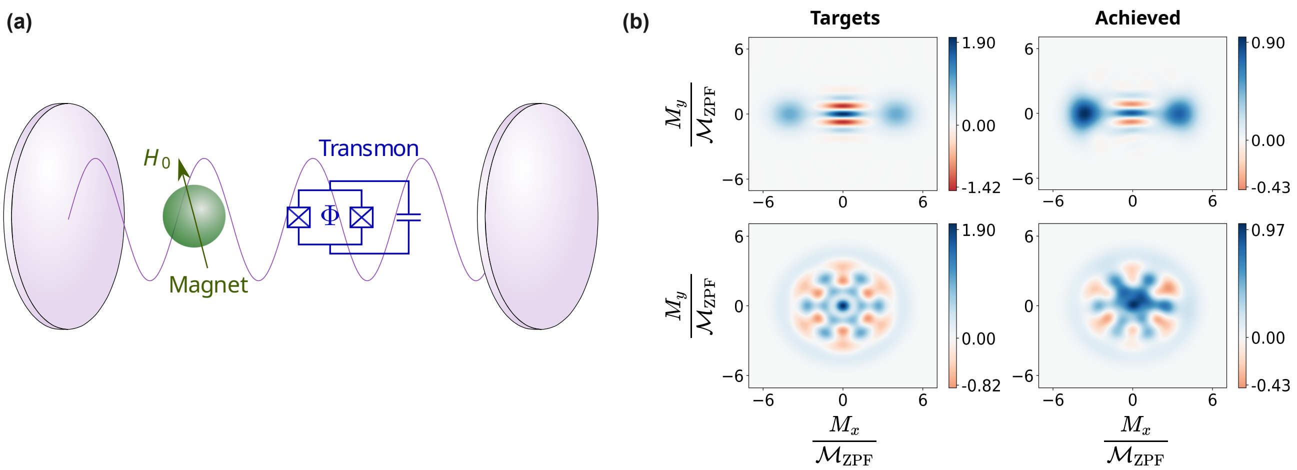

Figure 1: (a) A setup consisting of a microwave cavity mediating an interaction between a magnet and a superconducting transmon. The transmon is used to generate an arbitrary quantum state of the magnons. (b) Comparison of Wigner functions (a quasi-probability distribution) of two target states and the corresponding states achieved by the protocol. Here, M_x and M_y are the x and y components of the magnetization and the scale of the figure $\mathcal{M}_{\text{ZPF}}$ is the vacuum fluctuations of M_x and M_y. The achieved states maintain the coherence fringes, despite magnon dissipation. Figure adapted from my paper, Ref. [14].

Complementary to quantum state generation, it is required to have a method to perform *quantum measurements* on magnons. States containing a small number of magnons can be measured using a superconducting transmon[18,19], however this method lacks scalability and introduces additional dissipation. These issues are not present in measurements based on Brillouin light scattering[20,21], i.e. inelastic scattering of optical photons by magnons. Using measurements on the scattered photons, I developed a protocol to perform **quantum tomography** of magnons[9], i.e. estimate their density matrix. I analyzed the setup shown in Fig. 2(a) where a large coherent optical light is scattered by magnons, while squeezed light is used to reduce the noise in the output. Data analysis on scattered light using the *maximum likelihood principle* gives an estimate of the state of the magnons, shown as Wigner functions in Fig. 2(b). For a very low signal-to-noise ratio (SNR), the protocol still manages to predict the 'classical' component of the magnon state, given by the peak of the probability distributions. The protocol achieves high fidelity of reconstruction even when signal-to-noise ratio (SNR) is 1, limited primarily by computational requirements.

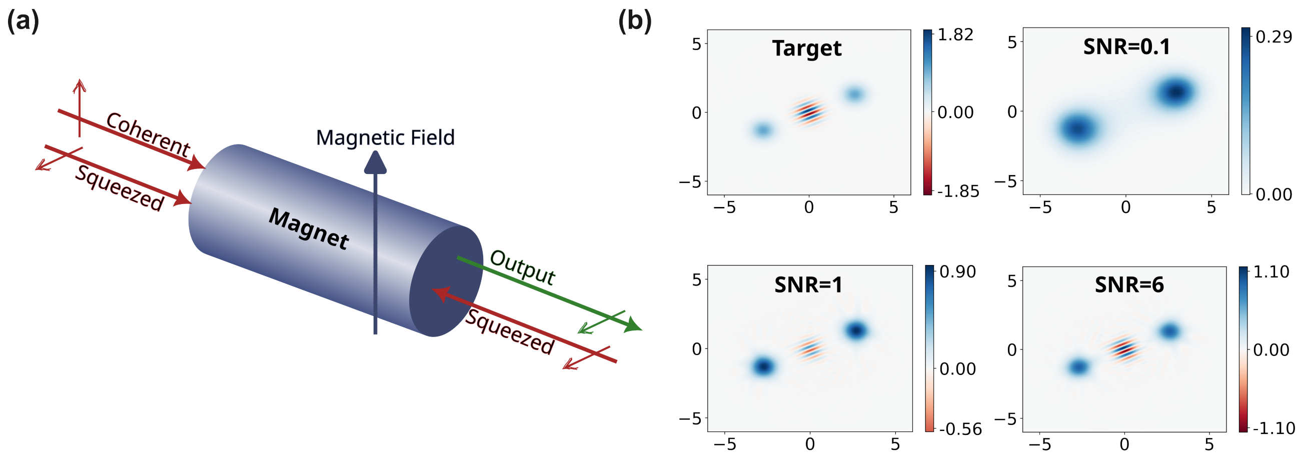

Figure 2: (a) A magnet is subjected to optical light, a large coherent component that scatters off magnons and squeezed photons to reduce output noise. The state of the magnons is estimated based on the (homodyne) measurements of the output photons. (b) For a given assumed state of the magnons, a cat state, the predicted states are shown for different values of signal-to-noise ratios (SNRs). Figure adapted from my paper, Ref. [9].

Future Plans: My research output so far sets up theoretical foundations to study and manipulate magnons in a quantum domain. Building up on them, I am currently interested in understanding microscopic properties of magnons and developing applications for quantum magnonics. This proposal on quantum magnon transport allows for improving our understanding of magnon coherence and more specifically, how quantum information is lost/preserved in a magnet. It also gives an avenue to apply and adapt methods from quantum transport of electrons, quantum communication, and open quantum systems to magnonics. I aim to develop such methods further and tailor them to be applicable to solid-state systems.

Collaboration Experience: Throughout my career, I have collaborated with several experimentalists, including Prof. Hans Hübl (Munich), Dr. Alexy Karenowska (Oxford), Prof. Roland Nagy (Erlangen), and Dr. James Haigh (Cambridge). I have an international research experience, having conducted long-term research in Germany, the Netherlands, France, and India, along with two short-term visits to Japan. I have worked with international collaborators from UK, China, and Iran.

Research Plan: **Quantum Transport of Magnons in Ferromagnetic Insulators**

Scalable quantum architectures require integration of multiple units[22,23] not only to increase computational power but also to perform diverse tasks such as storage, logic, and sensing. Such units must then communicate via **quantum channels**[24,25] that serve to transfer qubits and generate entanglement between them. For long-distance (kilometers) communication, optical photons are essential due to their uniquely long coherence lengths. However, their high frequency (>100 THz) makes them difficult to couple with low frequency ($\ll 1$ THz) devices commonly used for computation. For **near-device communication**, where such long coherence lengths are unnecessary, low frequency alternatives to photons are highly desirable[25].

Ferromagnetic insulators (FIs) support low-loss magnons that are promising as information carriers in a quantum channel for several reasons. Magnons couple to a variety of quantum systems, such as superconducting qubits[26,27], microwaves[28,29], nitrogen-vacancy (NV) centers[30–33], phonons[34], and optical light[35–37], allowing for communication between different quantum technologies as depicted in Fig. 3. There are evidences supporting macroscopic coherence lengths of magnons[18,19], including the demonstration of quantum superposition in a sub-mm magnet. There are several low-loss FIs which are promising materials for building quantum channels, such as Yttrium Iron Garnet (YIG), chiral Mott insulator Cu_2OSeO_3, organic compound $V[TCNE]_x$, and 2D van der Waal materials like CrX_3. To realize magnon-mediated quantum communication, it is essential to **understand and control magnon transport** in a quantum regime.

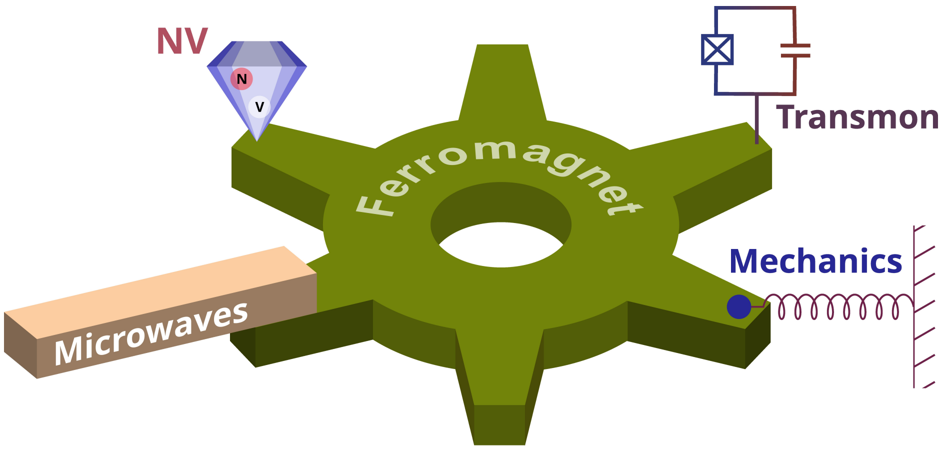

Figure 3: Magnons in an FI can mediate communication between different qubits, here exemplified by a Nitrogen-vacancy center in a diamond, a superconducting transmon circuit, a mechanical oscillator, and a microwave cavity.

Objectives: To develop a theory of quantum transport of magnons, and methods to analyze quantum communication mediated by magnons.

Concretely, the proposal aims to

1. *[Coh]*: find an expression for the quantum coherence length of magnons in terms of material and impurity parameters.
2. *[Wave]*: model the errors suffered by a propagating quantum wavepacket of a magnon.

3. *[Ent]*: analyze entanglement generation between remote qubits communicating via magnons.

State-of-the-art: **Classical transport** of magnons over mm-distances was demonstrated using *electrical measurements*[38–40], and has been studied extensively. In these studies, magnon transport was found to be significantly different than the electronic case because of their bosonic nature and a non-monotonic dispersion relation that can lead to unique phenomena such as spontaneous Bose-Einstein condensation[41].

As electrical measurements are incoherent, performing studies on quantum transport requires **quantum interfaces** to magnons. A possible interface is provided by the *superconducting transmon* which was used to generate and measure superposition of magnons[18]. In the same setup, I showed how to generate an arbitrary given quantum state of the magnons[14]. However, transmons have low spatial resolution limiting their application in transport, which typically requires point-to-point measurements. Nanoscale resolution along with high sensitivity can be achieved using *NV centers*[30–33], although their application to quantum measurements of magnons is not yet developed[33]. On the other hand, *optical photons* can achieve sub-micron resolution for magnon measurements[20,21] and I proposed a protocol to perform quantum tomography of magnons using them[9].

An important application of quantum transport theory is a microscopic analysis of remote **entanglement generation** mediated by magnons. It was proposed that magnons can be used to entangle two distant spin qubits[42,43], however such proposals require strong magnon-qubit coupling that is yet to be demonstrated. In contrast, *entangling protocols* used in quantum communication via optical photons can work even at weak qubit-photon coupling[44–46], as I discussed recently with microwave cavities being qubits[16]. An example is the so-called Barrett-Kok protocol[45] which has been demonstrated in optical fibers[47,48]. While optical photons are not suitable for near-device communication, as argued above, these protocols can be adapted for most bosonic channels including magnons.

Methodology: Here, I discuss the methods used for the three aims mentioned in Objectives, along with risk management. The timeline is shown in Fig. 4 with further details to follow.

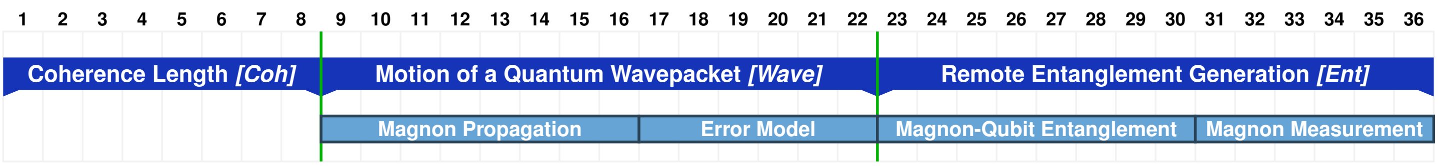

Figure 4: A Gantt chart showing the monthly timeline of each module and sub-modules.

Quantum Coherence Length of Magnons [Coh] *8 months*

The length of a magnon communication channel is limited by the quantum coherence length of magnons. I will calculate this coherence length by applying **Keldysh formalism** on a microscopic model of a ferromagnet, as shown in Fig. 5.

The Hamiltonian includes spin-spin interactions[49], namely exchange interaction that aligns nearby spins, long-range dipole-dipole coupling, and Dzyaloshinskii-Moriya interaction (DMI). These interactions can be solved to give the spatial distributions of the magnon modes[49]. At

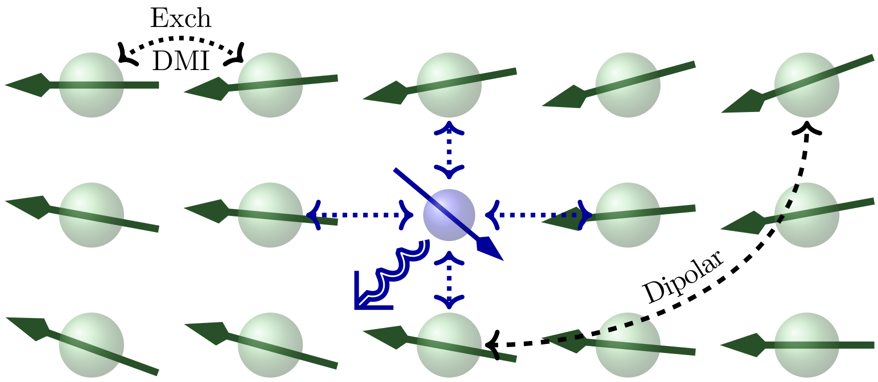

Figure 5: The microscopic model of an FI, including spin-spin interactions and magnetic impurities. The impurity can dissipate into a bath consisting of magnons and phonons.

cryogenic temperatures, dissipation of magnons is dominated by magnetic impurities[50–52] as opposed to intrinsic mechanisms being dominant at room temperature.

Applying Keldysh formalism, I will calculate the Green's functions, i.e. spatio-temporal correlations, of ferromagnetic spins. Notably, the spatial decay of the Green's functions will give the magnon coherence length. I will find the dependence of this coherence length on the direction of magnon and the ground state magnetization, providing a knob to tune transport.

I will apply this theory to low-loss FIs that are promising for quantum magnonic applications, particularly YIG and Cu_2OSeO_3.

Risk Management: If it becomes infeasible to solve the Keldysh equations of motion analytically, then a semi-numerical approach will be employed. The coherence length is estimated via a numerical integral over the scattering channels and a statistical average over impurity locations.

Quantum Wavepackets of a Magnon [Wave] *14 months*

Information through any quantum channel must be encoded in quantum wavepackets[53,54], that may consist of superpositions of semi-classical waves. Given a wavepacket, I will find the dominant forms of errors using methods from **open quantum systems**[55,56].

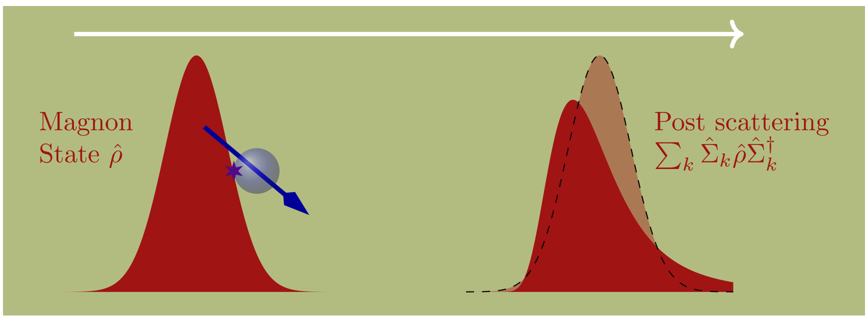

Figure 6: A propagating wavepacket of magnons interacts with impurities, suffering information loss which is modelled using 'Kraus' operators $\hat{\Sigma}_k$.

Propagation (8 months): The motion of a magnon wavepacket is primarily governed by its dispersion relation and stochastic scattering by impurities. I will model a single-impurity scattering, as shown in Fig. 6, using the Nakazima-Zwanzig equation[55,56] that gives a *stochastic evolution of magnons* after tracing out the impurity. This model will give an effective evolution of the magnon's density matrix, $\hat{\rho} \to \sum_k \hat{\Sigma}_k \hat{\rho} \hat{\Sigma}_k^\dagger$ where each Kraus operator $\hat{\Sigma}_k$ corresponds to different types of losses including loss of particle and coherence. Simulating multiple scattering events, I will numerically find the fidelity of how closely a magnon wavepacket maintains its original form as a function of the distance it has travelled. This fidelity is a measure of the robustness of a given wavepacket.

Error Model (6 months): For transporting information, a magnon must be encoded as a flying qubit. An encoded wavepacket is a generic superposition of $|\psi_0\rangle$ and $|\psi_1\rangle$ that are pre-defined wavepackets corresponding to the bits 0 and 1 respectively. Such a superposition can undergo different types of errors during its motion, including bit-flip, phase-flip, and information loss to outside the superposition space. I will find the *probability per unit length* of these errors depending on the chosen basis, $\{|\psi_0\rangle, |\psi_1\rangle\}$. The probabilities are found by numerically solving the stochastic evolution of magnons, as discussed in *Propagation*, for an arbitrary encoded wavepacket. These probabilities will then be used for optimization to mitigate errors, e.g. to find a pair $\{|\psi_0\rangle, |\psi_1\rangle\}$ least susceptible to bit flips.

Risk Management: Solving the stochastic quantum equations directly, e.g. via the package QuTiP, may turn out to be too computationally intensive. In that case, I will employ compact data structures to represent quantum states, in particular tensor networks[57] and Boltzmann machines[58], using existing libraries[59,60]. Secondly, if it turns out that either the bit-flip or the phase-flip errors are too high, I will use bosonic codes consisting of multiple magnons to mitigate these errors[17], similar to my work in microwave cavities[16].

Remote entanglement generation [Ent] *14 months*

Essentially all quantum communication protocols require an entangled state between the communicating parties[61], exemplified by the two qubits in Fig. 7. I will find the fidelity of entanglement generated via magnon-mediated communication.

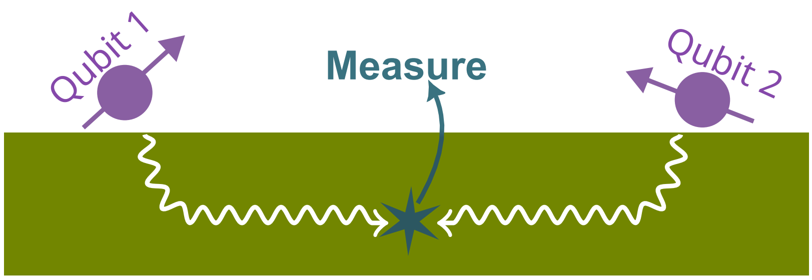

Figure 7: The BK-protocol to entangle two distant qubits involves generating magnon-qubit entanglement and a joint measurement on the two magnon waves.

I will consider NV centers as qubits and the Barrett-Kok (BK) protocol of entanglement generation as discussed above in State-of-the-Art. However, the following framework will be applicable to other qubits and entangling protocols as well. Entanglement is generated in two steps:

Magnon-Qubit Entanglement (8 months): NV centers are initialized according to the BK-protocol[45]. An excitation in NV can decay into the magnons via the dipolar interaction[33]. This forms an entangled state where the excitation can be in NV or in the form of a magnon wavepacket. Using the **input-output theory**[62], I will find the efficiency of this decay and the

spatial wavepacket of the generated magnon.
If an NV has decayed into the magnet, a magnon will propagate to the center of the two parties as shown in Fig. 7. Magnon motion away from the center can be suppressed using other magnets on top of the magnon communication channel[63,64]. Using the model of magnon propagation discussed above in *[Wave]*, I will calculate the probability of errors suffered by the propagating magnon.
Magnon Measurement (6 months): A measurement in the center of the two parties can reveal either 0, 1, or 2 magnons, depending on how many NVs have decayed. Following the BK-protocol, if only one magnon is measured, then an entangled NV-NV state is heralded, i.e. measurement induces a collapse of the joint state of the NVs into an entangled state. For other measurement outcomes, the protocol is restarted. A quantum measurement of the magnons can be performed using a superconducting transmon[18,19], optical light[9,20,21], or a third NV center[30–33]. I will find the efficiency of these measurements and compare with each other.
Risk Management: If either the magnon-qubit entanglement or magnon measurement is inefficient for entanglement generation, I will analyze entangling protocols designed for noisy channels[65,66] using the same theoretical tools as discussed here.

Impact: This project will have a high impact on two scientific fields:

- **Magnetism**: The recent demonstration of magnon quantization, along with several emerging ideas for quantum magnonic applications, led to a growing interest in understanding magnetism at a quantum level. A quantum transport theory of magnons will complement existing methods for magnon manipulation and measurements, laying the foundations for magnonic implementations of quantum computing. This project will contribute not only to the analyses of such implementations but also to comparison with other quantum technologies.
- **Quantum Computing**: As quantum channels are essential components of nearly all scalable quantum architectures, there is a need to find suitable information carriers, particularly for near-device communication. Developing magnons as effective carriers opens possibilities for implementing such communication algorithms and building complex quantum architectures. The framework developed in this project can further lead to new communication protocols tailored to solid-state quantum channels.

Dissemination: I aim to publish in high-impact journals appropriate for this work such as *Phys. Rev. Lett.*, *Phys. Rev. B*, *J. of Phys.* and *Quantum Sci. Tech*. I plan to disseminate this research in magnetism conferences such as *Magnonics* and *Spin Mechanics* that I have attended multiple times, along with quantum information conferences such as *WQRN* and *QIP*. I will put all of my papers on *arXiv* before submitting to journals for open access. I will upload the codes developed during the projects on my GitHub account[1] for further development by other researchers. I will use my website[2] to publish accessible summaries of my projects aimed at non-specialists.

[1] github.com/sancharsharma
[2] sancharsharma.com

1. A.V. Chumak et al. *IEEE Transactions on Magnetics* 58.6 (2022).
2. A. V. Chumak et al. *Nature Physics* 11.6 (2015).
3. Sanchar Sharma, Yaroslav M. Blanter, and Gerrit E. W. Bauer. *Phys. Rev. B* 96 (2017).
4. J. A. Haigh et al. *Phys. Rev. B* 97 (2018).
5. Sanchar Sharma, Yaroslav M. Blanter, and Gerrit E. W. Bauer. *Phys. Rev. Lett.* 121 (2018).
6. Sanchar Sharma et al. *Phys. Rev. B* 99 (2019).
7. Fran Šimić et al. *Phys. Rev. B* 101 (2020).
8. Jasmin Graf et al. *Phys. Rev. Res.* 3 (2021).
9. Sanchar Sharma, Silvia Viola Kusminskiy, and Victor A. S. V. Bittencourt. *Phys. Rev. B* 110 (2024).
10. Tahereh Sadat Parvini et al. arXiv:2409.10659.
11. Tao Yu et al. *Phys. Rev. Lett.* 124 (2020).
12. Tao Yu et al. *Phys. Rev. B* 101 (2020).
13. Sanchar Sharma et al. *Phys. Rev. B* 103 (2021).
14. Sanchar Sharma, Victor A S V Bittencourt, and Silvia Viola Kusminskiy. *Journal of Physics: Materials* 5.3 (2022).
15. Martijn Dols et al. *Phys. Rev. B* 110 (2024).
16. S. Siddardha Chelluri et al. *Manuscript in preparation* (2024).
17. B M Terhal, J Conrad, and C Vuillot. *Quantum Science and Technology* 5.4 (2020).
18. Da Xu et al. *Phys. Rev. Lett.* 130 (2023).
19. Dany Lachance-Quirion et al. *Science* 367.6476 (2020).
20. A.S. Borovik-Romanov and N.M. Kreines. *Physics Reports* 81.5 (1982).
21. Thomas Sebastian et al. *Frontiers in Physics* 3 (2015).
22. David P. DiVincenzo. *Fortschritte der Physik* 48.9-11 (2000).
23. H. J. Kimble. *Nature* 453.7198 (2008).
24. David Awschalom et al. *PRX Quantum* 2 (2021).
25. Georgios M. Nikolopoulos and Igor Jex. Springer Berlin, Heidelberg, 2014.
26. Yutaka Tabuchi et al. *Science* 349.6246 (2015).
27. Marios Kounalakis, Gerrit E. W. Bauer, and Yaroslav M. Blanter. *Phys. Rev. Lett.* 129 (2022).
28. Yutaka Tabuchi et al. *Phys. Rev. Lett.* 113 (2014).
29. Xufeng Zhang et al. *Phys. Rev. Lett.* 113 (2014).
30. Alberto Boretti et al. en. *Beilstein J Nanotechnol* 10 (2019).
31. Francesco Casola, Toeno van der Sar, and Amir Yacoby. *Nature Reviews Materials* 3.1 (2018).
32. Iacopo Bertelli et al. *Science Advances* 6.46 (2020).
33. C. Gonzalez-Ballestero, Toeno van der Sar, and O. Romero-Isart. *Phys. Rev. B* 105 (2022).
34. Richard Schlitz et al. *Phys. Rev. B* 106 (2022).
35. A. Osada et al. *Phys. Rev. Lett.* 116 (2016).
36. Xufeng Zhang et al. *Phys. Rev. Lett.* 117 (2016).
37. J. A. Haigh et al. *Phys. Rev. Lett.* 117 (2016).
38. L. J. Cornelissen et al. *Nature Physics* 11.12 (2015).
39. Y. Kajiwara et al. *Nature* 464.7286 (2010).
40. L. J. Cornelissen et al. *Phys. Rev. B* 94 (2016).
41. S. O. Demokritov et al. *Nature* 443.7110 (2006).
42. Masaya Fukami et al. *PRX Quantum* 2 (2021).
43. Luka Trifunovic, Fabio L. Pedrocchi, and Daniel Loss. *Phys. Rev. X* 3 (2013).
44. C. Cabrillo et al. *Phys. Rev. A* 59 (1999).
45. Sean D. Barrett and Pieter Kok. *Phys. Rev. A* 71 (2005).
46. Koji Azuma et al. *Rev. Mod. Phys.* 95 (2023).
47. H. Bernien et al. *Nature* 497.7447 (2013).
48. B. Hensen et al. *Nature* 526.7575 (2015).
49. Daniel D. Stancil and Anil Prabhakar. New York: Springer, 2009. ISBN: 978-0-387-77864-8.
50. H. Maier-Flaig et al. *Phys. Rev. B* 95 (2017).
51. Marco Pfirrmann et al. *Phys. Rev. Res.* 1 (2019).
52. S. Kosen et al. *APL Materials* 7.10 (2019).
53. B. Brecht et al. *Phys. Rev. X* 5 (2015).
54. Joseph M. Lukens and Pavel Lougovski. *Optica* 4.1 (2017).
55. H. P. Breuer and F. Petruccione. Oxford University Press, 2002.
56. Ángel Rivas and Susana F. Huelga. Springer Berlin, Heidelberg, 2012.
57. Román Orús. *Annals of Physics* 349 (2014).
58. Roger G. Melko et al. *Nature Physics* 15.9 (2019).
59. Martíín Abadi et al. www.tensorflow.org.
60. Adam Paszke et al. arXiv:1912.01703.
61. Michael A. Nielsen and Isaac L. Chuang. Cambridge University Press, 2010.
62. C. W. Gardiner and M. J. Collett. *Phys. Rev. A* 31 (1985).
63. Andrii V. Chumak, Alexander A. Serga, and Burkard Hillebrands. *Nature Communications* 5.1 (2014).
64. K. S. Das et al. *Phys. Rev. B* 101 (2020).
65. J. I. Cirac et al. *Phys. Rev. A* 59 (1999).
66. S. J. van Enk, J. I. Cirac, and P. Zoller. *Phys. Rev. Lett.* 78 (1997).