Light-matter interaction has attracted intense research interest ranging from quantum sensing to quantum information science (such as quantum computing and quantum networks). I focus on the dynamical control of light-matter interaction to achieve **robust generation and manipulation of multi-mode quantum entanglement, with both atomic and optical qubits**. Traditionally, extending single-mode entanglement to multi-mode entanglement is predominantly studied with multiple entanglement sources, which lacks scalability. I researched for more compact and direct means of generating multi-mode entanglement in spatial and frequency domains that will make it more scalable and stable, resulting in more complex protocols. Meanwhile, the miniaturization of entanglement generation and manipulation is an essential step toward practical applications. I investigated light-matter interaction in an integrated system (an atom chip) that offers additional controls to generate novel types of entanglement and high-precision probes in different scenarios. **My long-term goal** is to explore multi-mode entanglement from light-matter interaction to advance quantum science and technology with integrated systems.

I want to summarize the key contributions of my research to date as follows:

1. **Developed an atom-chip technique with dynamical control of atomic qubits:** A significant challenge of using atom chips for quantum science and technology is the lack of dynamic control. For example, traditional atom interferometers on chip [1] used two static traps containing single-state atoms. I developed a series of atom chip techniques to distribute atoms within an initial single wave-packet with a single atomic state into multiple wavepackets with two internal atomic levels (qubits) [2–5], which enable dynamic control over various internal and external degrees of freedom. More specifically, I realized a self-interfering clock (compromising two atomic spin states, acting as an atomic qubit) as a which-path witness [2, 3], which is the first time an atom clock has been put on a spatial superposition. I used the entanglement between the spin and momentum states for a spatial dynamical decoupling technique that increases the coherence length, realizing a long-sought complete Stern-Gerlach interferometer, which is important for studying quantum gravity [4]. I achieved a T^3-Stern-Gerlach matter-wave interferometer, whose phase scales with the cube of the time that the atom spends in the interferometer [5], instead of the square of time in traditional atom interferometers. These techniques allow a high-precision tool for the quantum manipulation of atomic qubits and for the surface probe.
2. **Investigated the intersection between entanglement and topology with atomic qubits:** Combing entanglement and topology enables novel quantum states with topological protection that is immune from disturbances. I investigated such a combination by creating topological structures with the entangled multiple modes [6–8]. Specifically, I entangled the internal (spin) and external (spatial) degrees of freedom with atomic qubits and applied the geodesic rule to search for geometric phase and topological effects [6]. I reported a previously unshown experimental confirmation of the geodesic rule for a noncyclic geometric phase and demonstrated, with high precision, the predicted phase sign change and π jumps. I furthermore studied the entanglement and geometric phase-induced momentum quantization in an atomic interferometer [7, 8]. The geodesic rule and the sharp phase/momentum jumps can be applied to obtain the weak signals in internal population distributions and external field potentials. The noncyclic operations can be done faster than cyclic operations and facilitate additional control over relevant applications involving geometric phase and topology, such as geometric quantum computing.
3. **Explored multi-mode entanglement generation and manipulation of optical qubits:** Multi-mode nonclassical states of light are an essential resource in quantum information science. I explored the multi-mode nature of quantum entanglement in spatial and frequency domains with a four-wave mixing (FWM) process in hot rubidium vapor [9–16]. Utilizing the strong light-atom interaction in free space, I realized frequency-controllable entangled beams [9, 11] and used entangled beams to construct a quantum interferometer [10]. In the spatial domain, I used spatial light modulators [12] to image multi-spatial modes with quantum noises and realized a temporally multiplexed storage of images in a gradient echo memory [13]. In the frequency domain, I used electo-opto modulators (EOMs) and phase modulations to build the correlation among different frequency-binned modes, which provides a compact and direct way to generate a high-dimensional quantum network [16]. Using a phase-conjugate resonator, I demonstrated an optical frequency comb [14] and observed dissipative Kerr solitons [15]. FWM in atomic vapor is a powerful platform for studying multi-mode optical entanglement and its applications.

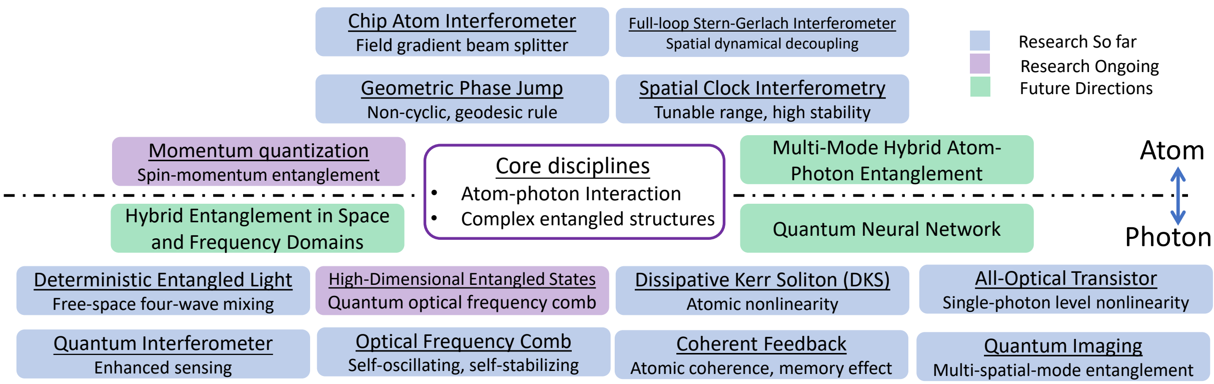

Fig. 1. Overview of my research so far, research ongoing, and future plans.

1 Multi-Mode Atomic Entanglement with an Atom Chip

An atom chip miniaturizes electric and magnetic potentials to build versatile traps and guides for atoms at a scale of μm. It offers a high-level control of spatial and temporal fields, such as high magnetic field gradients, fast timing, and high accuracies. I used pulsed magnetic field gradients generated by currents in atom chip wires (made of gold, with a height of 2μm, a width of 40μm, and a length of 1mm) on top of a silicon wafer and radio-frequency transitions between two internal atomic levels [17]. I transformed atoms into a superposition of a continuous wide range of internal population states and external momentum states.

1.1 Increasing Coherence Length Making the atom chip technique more stable for quantum manipulation and more sensitive for quantum sensing requires suppressing different decoherence sources from the environment or more fundamental origins. Dynamical decoupling is a quantum control technique used in many quantum computing and quantum memory protocols to suppress decoherence by taking advantage of periodic sequences of instantaneous control pulses, whose net effect is to average the unwanted system-environment coupling to approximately zero. I implemented a spatial dynamical decoupling technique to decouple the atom chip operations from the electronic and magnetic noises, increasing the coherence length and allowing for larger-scale integration of atomic qubits and advanced quantum manipulations and detections [4], e.g., for the study of quantum gravity.

1.2 Intersection between Entanglement and Topology To probe the intersection between entanglement and topology, I specifically studied the entanglement-induced geometric phase and momentum quantization. The spatial interference phase shows the geometric phase rigidity and π phase jump versus the internal population transfer, which otherwise shows a sinusoidal oscillation depending on the Rabi rotation angle Fig. 2b. I furthermore investigated entanglement and geometric phase-induced momentum quantization Fig. 2c [7, 8]. If I prepared the wave packets with maximum entanglement to enclose the origin of the Bloch sphere, the interference wavelength is quantized as the momentum kick from the atom chip changes, exhibiting the momentum quantization. In contrast, in the absence of the entanglement, the change of interference wavelengths became a continuous linear function. It has the potential technological advantages for geometric quantum gates. In addition, metrology can be made more sensitive due to the expected phase jumps, e.g., in measuring a gravitational potential.

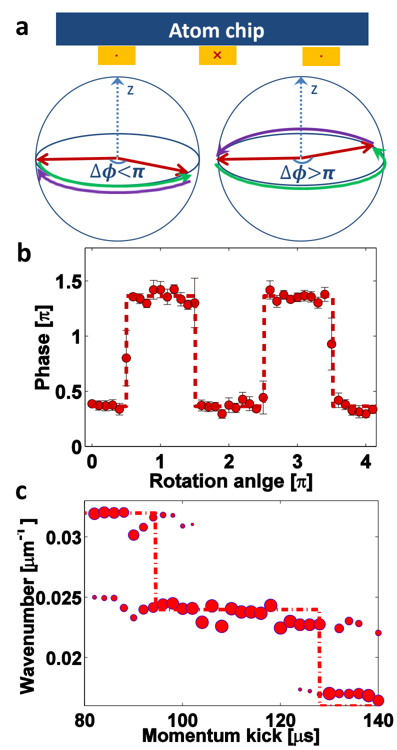

Fig. 2. **(a)**: The enclosed areas between Hamiltonians (green) and measurements (purple) yield geometric phases, controlled by the atom chip; **(b)**: the induced phase stability and π phase jump; **(c)**: the induced momentum quantization.

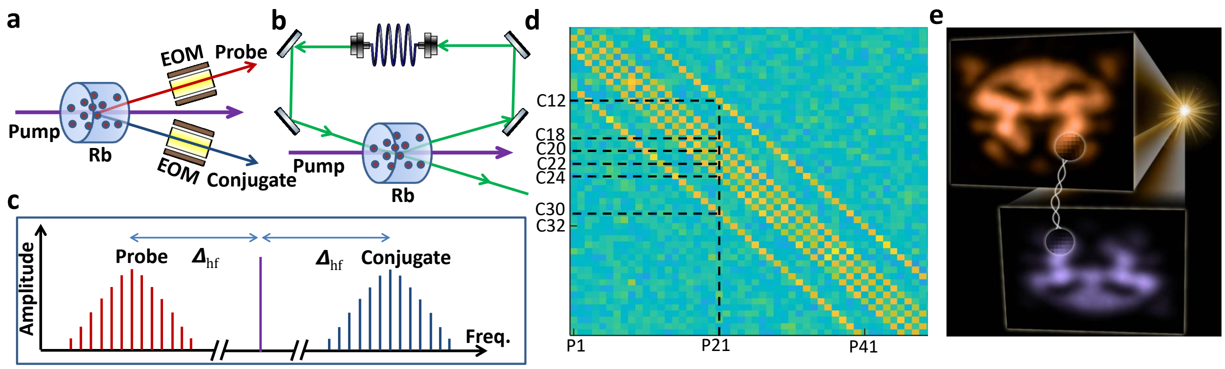

Fig. 3. **(a)**: Experimental setup of phase modulated twin beams out of the FWM in hot rubidium vapor. **(b)**: Schematic diagram of the phase-conjugate resonator with the FWM process in hot rubidium vapor. **(c)**: The schematic figure shows the output multi-mode spectra (optical frequency comb), which can be generated in the way presented in (b). **(d)**: Both twin beams contain 49 modes in the frequency domain depending on the bin size (100kHz) and the analyzed frequency bandwidth (0.05MHz-4.95MHz). I measured the XP covariance matrix of the twin beams via three-frequency phase modulations (100kHz, 300kHz, and 900kHz), which shows three double-off-diagonal structures of the correlations corresponding to ±1, ±3, and ±9 modes among 49 modes of both probe and conjugate. The black dashed lines guide the correlations between P21 and C12, C18, C20, C22, C24 and C30. **(e)**: The strong nonlinearity in FWM allows for multi-spatial-mode quantum correlation with hundreds of arbitrary spatial modes. Here is an example of two entangled cats' images.

2 Multi-mode Optical Entanglement with an Atomic Vapor

Atomic vapor combines the advantages of an atomic ensemble, such as deterministic atomic resonance with a moderate inhomogeneous broadening around 500MHz and atomic coherence, and of a condense-matter ensemble, such as high particle density ($10^{19}/m^3$). The light-atom interactions in the atomic vapor exhibit strong nonlinearities, which can support parallel spatial and frequency modes. Thus, I used the strong light-atom interaction in a hot rubidium vapor to generate entangled lights via an FWM process [9–11] and investigated the multi-mode nature of the entanglement in the spatial and frequency domains.

2.1 Multi-mode Entanglement in Frequency Domain The quantum entanglement emitted from FWM (Fig. 3a) is exhibited as entanglement between the probe and conjugate beams. I phase modulated the probe and conjugate beams by EOMs to generate correlation among different modes (Fig. 3c). I binned each mode with 100kHz (the bandwidth of 0.05MHz-4.95MHz is analyzed), and the three-frequency (with 100kHz, 300kHz, and 900kHz) modulation is applied. In the correlation matrix (Fig. 3d), the probe and conjugate beam exhibit 49 modes. The phase modulations created three double-off-diagonal correlation structures corresponding to the correlation between the 1st-order, 3rd-order, and 9th-order neighboring modes. Namely, each mode in one beam is correlated with every ±1, ±3, and ±9 mode in the other beam. Without phase modulation, there will be a one-by-one correlation between the probe and conjugate modes, resulting in a diagonal line in the correlation matrix. It provides a compact and direct way to generate a high-dimension quantum network for different quantum computing [18] and distributed quantum sensing tasks [19]. To further illustrate the multi-mode properties of FWM output spectra, I built a fiber-based phase-conjugate resonator (Fig. 3b) to generate optical frequency combs [14] and dissipative Kerr solitons [15].

2.2 Multi-mode Entanglement in Spatial Domain For a pair of the spatially extended probe and conjugate fields(Fig. 3e), the concept of entanglement can be applied not only to the entire images but also to their smaller details. I realized an imaging technique using the spatial-multi-mode using quantum noise projected by a spatial light modulator (SLM) [12], allowing for imaging techniques that can surpass classical limits on resolution or signal-to-noise ratio. For quantum memories in quantum network protocols, I studied the storage and retrieval of multi-spatial-mode images in an atomic vapor using the gradient echo memory protocol [13]. Moreover, I demonstrated that multiple images could be stored and retrieved at different times, allowing the storage of a short movie in an atomic memory. This opens the way to multiplexing simultaneously in time and in space for future quantum memory applications. The high degree of spatial entanglement demonstrates that the system is ideal for parallel quantum information protocols.

Future Research

My work on multi-mode entanglement with atomic and optical qubits has shown the potential for advanced quantum control. In what follows, I will outline three strategic areas in my future plan, among others.

1. **Hybrid Entanglement in Spatial-and-Frequency Domains:** Entanglement in multiple degrees of freedom enables quantum information processing with higher channel capacity and is more compatible with diverse quantum networks. Moreover, it promises enhanced violations of nonlocality in quantum systems and improved sensitivities in distributed quantum sensing. I plan to build hybrid entanglement with optical qubits in space and frequency domains through two alternative ways: (1) combined application with EOMs to modulate the qubits in the frequency domain and SLM to modulate the qubits in the space domain, as shown in Fig. 3(a,d,e), which results in a product value of the total mode number; (2) Multi-spatial-mode optical frequency comb generated in phase conjugate resonator, where a **multi-mode fiber** with minimal loss and compatible with complex spatial modes is used in Fig. 3(b).
2. **Multi-Mode Atom-Photon Entanglement** Photons are ideal for distributing quantum information between remote nodes for their traveling speed as light and little environmental disturbance. Meanwhile, atoms with appropriate internal structures allow for precise control of individual qubits. A single atom-photon qubit interfering with another single atom-photon qubit has been reported [20]. I plan to extend single-mode entanglement to the multi-mode case by coupling the multi-mode atomic and optical qubits. First, I plan to prepare two 1D arrays of atomic qubits under a linear external potential with the energy separation coupled with multi-mode frequency optical qubits with two different locations. The multi-mode entanglement will be confirmed by the multi-mode interference. A high-dimensional network requires a 2D matrix or 3D lattice of atomic qubits or a multi-frequency phase modulation in optical qubits.
3. **Quantum Neural Network (QNN):** Quantum neural networks enable applications beyond what is possible with their classical counterparts. The critical ingredient of a quantum artificial neural network is the artificial quantum neurons with multiple interconnections [21], which perform both linear and nonlinear transformations for the input signals. I will use multi-mode entanglement to realize parallel calculations to realize a QNN. A bottleneck in realizing ONNs is the lack of nonlinear optical activation functions. I realized optical logic gates through coherent feedbacks [22] and an ultralow-light-level all-optical transistor in rubidium vapor with a gain of 5×10^6 [23], which paved the way for QNNs.

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