The Nucleus **63**, No. 1 (2026) 1-10

https://doi.org/10.71330/thenucleus.2026.1495

www.thenucleuspak.org.pk

The Nucleus
ISSN 0029-5698 (Print)
ISSN 2306-6539 (Online)

Quantum Information Processing with Alkali Atoms: A Narrative Review

Muhammad Rashid[1*], Ayaz Husnain[2], Hafiza Ayesha Anwar[3], Aamir Abbas[4]

[1]*Department of Physics, University of Auckland, Private Bag 92019, Auckland, New Zealand*

[2]*Department of Material Science and Nanotechnology, University of Milano Bicocca, Piazza dell'Ateneo Nuovo, 1, 20126 Milano MI, Italy*

[3]*Department of Physics, The University of Faisalabad (TUF), Sargodha Road, 38000, Faisalabad, Punjab, Pakistan*

[4]*Department of Physics, University of Agriculture (UAF), Faisalabad, 38040, Punjab, Pakistan*

ABSTRACT

Quantum information processing is a promising way that deals with the aspects of superposition, entanglement, computation using coherence, communication, and sensing. This review is an analysis of how alkali Rydberg atoms can be used in quantum information processing. The leading candidates are the alkali atoms, as they have a simple electronic structure, transitions that are well characterized, and which can be laser-cooled and trapped. Important mechanisms, such as EIT, dipole-dipole interactions, and Rydberg blockade, are necessary to achieve high-fidelity quantum gates, photon-photon interactions, and long-lived quantum memories. Experimental devices such as magneto-optical traps, optical tweezers, optical lattices, and warm vapor cells have made it possible to use a controllable atom-photon interface and scalable architecture. In the recent development of laser and microwave control methods, the time of coherence, state-transfer, and single-atom addressability have been enhanced. Such challenges include decoherence due to spontaneous emission, motional dephasing, and technical issues in trapping stability and laser linewidth. This review concludes that alkali Rydberg atoms, especially rubidium and cesium, are of relevance in scalable fault-tolerant quantum computing and quantum simulation, and represent the meeting of basic quantum science with new technology uses.

Keywords: *EIT, Fidelity, Laser cooling, QIP, Rydberg atoms, Rydberg blockade*

1. Introduction

Quantum Information Processing (QIP) has emerged as a transformative paradigm in modern physics aiming to exploit the principles of quantum mechanics. Recent advances in QIP using neutral atom platforms have established Rydberg arrays as one of the most promising architectures for scalable quantum technologies. Recent work demonstrates that Rydberg superatoms can be utilized for quantum computation and optical quantum technologies, providing new pathways for implementing quantum protocols [1]. Researchers have achieved quantum gate fidelity using rapid adiabatic passage schemes on Rydberg platforms. Fidelities over 0.9995 were attained by controlled-Z gates and over 0.999 by CCZ gates. For three-qubit gates, enhanced-robustness gate schemes were created [2]. Rydberg arrays of two species of atoms (rubidium plus cesium) exhibit interspecies Rydberg blockade and quantum state transfer, creating new opportunities to use ancilla-assisted quantum protocols [3]. New developments in trapping atoms and implementing gates, as well as quantum memory technologies that use Electromagnetically Induced Transparency (EIT) have shown how important alkali atomic systems are for quantum communication and information storage. Ongoing advancements in quantum memory systems employing EIT in warm atomic vapors demonstrate the storage of coherent light pulses with bandwidths nearing 200 MHz providing practical benefits for long-distance quantum communication [4]. More efficient quantum memory enhancement methods have also been demonstrated with a high efficiency of 34.3±8.4% and a high band of GHz-bandwidth and low-noise [5]. A recent advancement in EIT is nuclear spin-induced transparency (NSIT), in which optical fields are coupled to magnetic fields through spin-exchange interactions between the nuclear spins of noble gases and the electronic spins of alkali-metal atoms. NSIT has transparency windows many orders of magnitude narrower than traditional EIT, down to sub-mHz frequencies because nuclear spin coherence times are very long [6]. Such developments are significant improvements in EIT-based quantum memories; they improve efficiency, bandwidth, and coherence, which make it easier to implement in practice in long-distance quantum communication networks.

Rydberg atoms provide strong, controllable long-range interactions, enabling two-qubit gates, collective multiqubit encoding, light-atom interfaces, and quantum simulation systems [7]. Rydberg atom arrays are now a valuable synthetic quantum system which assists researchers to study many-body physics, exotic quantum phases and coherent dynamical phenomena. Quantum gates and quantum memories also employ them. Rydberg atoms have been used as synthetic quantum landscapes for controlling and probing coherent dynamics, where nine-site synthetic lattices enable nanoscale quantum walks, Bloch oscillations, and the controlled confinement of interacting particle pairs [8]. More complex studies of Rydberg arrays elucidate the properties of quantum phases and entanglement, demonstrating that ordered phases decay with thermal noise through conformal scaling equations that extend to moderate temperatures, including absolute zero [9]. Theoretical predictions and experimental procedures have been developed by the researchers in the realization of a supersolid phase in Rydberg tweezer arrays in terms of dipolar and van der Waals interaction enabling the explicit study of defect-mediated supersolid effects [10]. Rydberg atom arrays can be used to analyze strange phases, coherent dynamics, and other new many-body dynamics with unparalleled control and precision.

*Corresponding author: rmuh003@aucklanduni.ac.nz

QIP employs physical mechanisms such as EIT, Rydberg blockade, and dipole-dipole interactions to manipulate and control quantum states. These methods make it possible to advance applications in simulation, communication, sensing, and single-photon sources. Recent developments have led to the advances of large-scale quantum technologies because they demonstrated the robustness of Rydberg-EIT, the Rydberg blockade effect, and customized interactions between dipoles and dipoles. A fundamental building block for QIP is shown by schematic diagram in figure 1.

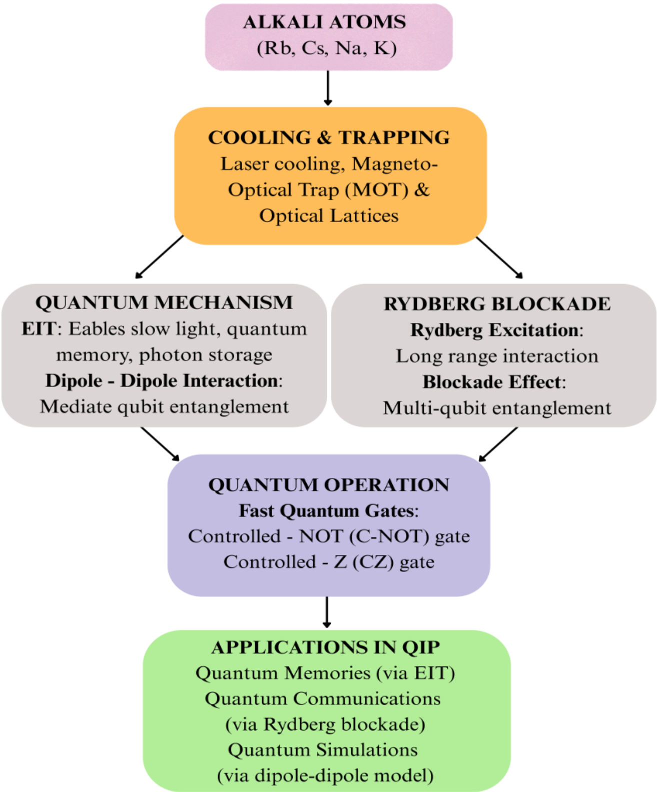

Fig. 1: Building block of quantum information processing.

2. Laser Cooling and Trapping

Laser cooling and trapping of neutral atoms has revolutionized experimental quantum physics by providing unprecedented control over atomic motion and internal quantum states. The neutral atoms are crucial in the recent quantum technologies in the form of magneto-optical traps (MOTs) and optical lattices as primary experimental instruments. MOTs permit the generation of ultracold atomic ensembles in high densities, whereas optical lattices permit the spatial localization of atoms and the creation of customized quantum states and mediated interactions [9]. Recent advances in quantum simulation and quantum computations involve the implementation of MOTs and optical lattices that enhance the coherence times and addressability. Hybrid platforms can have optical tweezer arrays that are more reconfigurable [11]. MOT-based cooling and optical lattice trapping are important in the construction of a scalable, well-controlled, and coherent neutral atom quantum system. Such techniques are a basis of entirely quantum technologies in the next generation, as well as quantum phase simulation, study of topological quantum matter, and fault-tolerant quantum computing structures [12].

3. Trapping Techniques for Alkali Rydberg Atoms

The ability to control, cool, and trap atomic alkali atoms in the highly excited states is based upon experimental techniques of trapping. These methods make possible specific research on collective quantum physics, strong interactions, and creation of scalable quantum technology materials. Magneto-optical traps and optical tweezers have emerged as crucial instruments for the creation and precise manipulation of ultracold Rydberg ensembles, driven by advancements in neutral-atom trapping. Alongside, ion-based and hybrid atom-ion trapping approaches enhance confinement capabilities by enabling greater precision and extended trapping times, though they also introduce distinct technical challenges.

3.1 Magneto-optical Traps (MOTs)

Magneto-optical traps are the main experimental methods for creating and modifying alkali Rydberg atoms. They are a crucial setting for the creation of dense and ultracold ensembles, which enable the investigation of collective quantum charges and strong forces. MOTs are crucial for cooling and trapping alkali Rydberg atoms, achieving extremely low temperatures and densities that facilitate strong interactions and allow for collective Rydberg state experiments. In more recent experiments, optical tweezers, optical lattices, and fiber optics explore improving the addressability and scalability of a single atom and trapped Rydberg superatoms to high-fidelity multipartite entangled states [13]. A new trapping method uses non-linearly polarized light vector polarizability to create robust, lossless forces on isolated Rydberg atoms, enhancing quantum simulation and hybrid atom-light states with position-dependent potentials [14]. These developments in trapping methods are opening the door for next-generation quantum simulation platforms and scalable Rydberg-based QIP.

3.2 Optical Tweezer Array Technologies

Optical tweezers have become a revolutionary instrument in neutral-atom quantum platforms providing high-precision trapping, reconfigurability, and scalability crucial for extensive quantum information processing. Neutral-atom platforms are now a leading architecture for large-scale QIP due to recent experimental advances in optical tweezer technology, which have significantly improved their scalability and control. Record-breaking performance metrics such as 12.6-second coherence times, 23-minute trapping lifetimes, and 99.98% imaging survival rates are achieved by scaling optical tweezer arrays to 6,100 neutral atoms in 12,000 sites [15]. Holographic metasurfaces have revolutionized optical tweezer generation enabling the creation of arrays with over 1000 trapped atoms demonstrating potential for scaling to 360,000 traps [16]. Advanced holographic procedures have demonstrated a high degree of control in optical tweezer arrays, making them useful in quantum science with an atomic array based on ultraprecision, with the intensity homogeneity being 0.3 percent [17]. These improvements underscore the rapid progress of optical tweezer technology, which is establishing neutral-atom arrays as a scalable and precise basis of next-generation QIP.

3.3 Trapping with Optical Lattices

Neutral atoms such as rubidium and cesium are trapped using optical lattices, which are created by interfering the laser beams and offer periodic trapping potentials with long trapping lifetimes essential to quantum technologies. The lattices form ordered large-scale atomic arrays to process quantum information with a site per quantum computation and simulation scalable quantum computation and simulation. The lattices consist of ordered large-scale atomic arrays, which can be simulated as qubits. They are periodically correlated, which is their instrumental aspect in simulating strongly correlated quantum systems, lattice gauge theories, and quantum phases with adjustable parameters that facilitate the study of various Hamiltonians and many-body dynamics [12, 18]. Spatial resolution below the diffraction limit has been realized with sub-wavelength lattice engineering, which has been useful in the control of tunneling rates and state-selective transport of quantum gates and coherent quantum walks. Site-resolved imaging has high fidelity single-atom measurements to correct errors and prepare states. The combination of optical cavities and lattices provides a high degree of efficiency in the process of atom-light coupling, making it possible to perform high-fidelity measurement of the quantum state of atoms and to generate entangled photons via photon interplay [19].

Optical lattices in combination with Rydberg excitation and blockade processes have made it possible to perform multi-qubit gate dynamics and collective entanglement schemes. The interactions mediated by Rydberg allow controllable interactions between more than nearest neighbors, which would enable strong entanglement between far-apart lattice sites in a scalable structure. This has given way to experimental realizations of fault-tolerant quantum computing systems using lattice regularity as an error-correcting code and logic qubits with high-fidelity [2, 20]. Optical lattices can serve as scalable quantum simulation platforms and scalable quantum computers. The combination of Rydberg regime and cavity quantum electrodynamics makes them an important step towards quantum control, enabling the simulation of complex quantum states, high-fidelity gates and scalable fault-tolerant quantum systems of the next generation of quantum technologies.

3.4 Ion and Hybrid Atom-Ion Trapping Approaches

Ion-based and hybrid trapping strategies, which offer longer trapping times and more precision but also present new technical difficulties, have become effective methods for containing and managing Rydberg systems outside of neutral-atom MOTs. Paul and hybrid atom-ion traps also make charged particles confinement and manipulation achievable, but they have several limitations such as decoherence effects and heating by ion micromotion and require sophisticated cooling and error reduction strategies [21]. Magnetic microtraps and electric fields have been used to trap Rydberg atoms, achieving stable MOTs with sub-micro kelvin temperatures and long trapping lifetimes [22]. Although resolving issues with stability and decoherence is still crucial to developing quantum technologies yet these trapping techniques jointly offer flexible platforms for investigating Rydberg interactions.

4. Fundamentals of Rydberg Atoms

The progress in the manipulation of Rydberg atoms has dramatically increased their application in QIP, especially the control of energy levels and entangling interactions. Recent experiments have enhanced the ability to electrically tune Rydberg levels, allowing for the tight control of resonance conditions and energy-level separation of Rydberg levels, which are crucial for strong quantum information encoding and transfer [23]. Rydberg blockade is still critical towards entanglement and multi-qubit gate control. High-fidelity creation of Bell and W states (fidelity >0.9995) in alkali atoms by quick adiabatic transit methods has been demonstrated in the Rydberg blockade region, and demonstrates the reliability and scalability of the mechanism to quantum computer architectures. In addition, new gate protocols like controlled-Z and Fredkin gates have also been demonstrated to be working reliably in the blockade regime with both global and local pulse techniques, reducing hardware complexity and scaling to larger sizes [24]. Dual-species Rydberg arrays system (using Rb and Cs) exhibit significantly higher interspecies Rydberg blockade as compared to single-species systems, enabling quantum state transfer and entanglement formation. This progress allows more lenient computational mechanisms and heterogeneous quantum computers [25]. These achievements make the Rydberg blockade a foundation of quantum computing with neutral atoms, and enable flexible multi-qubit gate models, scalable, heterogeneous quantum systems, and high-fidelity entanglement with Rydberg atoms.

4.1 Dipole-Dipole Interactions and van der Waals Forces

The short-range dipole-dipole interactions and the long-range van der Waals forces continue to contribute to strong tunable interatomic forces. Resonant dipole-dipole coupling has been experimentally demonstrated to allow fast entangling gates that do not depend on interatomic distance changes, and is found to be scalable to large-scale quantum devices. Besides the blockade mechanism, interatomic interactions among Rydberg atoms fundamentally determine the strength, tunability, and scalability of interactions required for implementing efficient quantum logic operations. The interactions between Rydberg atoms are dominated by two long-range potentials.

The van der Waals interaction between two neutral Rydberg atoms in the same electronic state scales is written as: $V_{vdW}(R) = -\frac{C_6}{R^6}$ where C_6 is the van der Waals coefficient and R is the internuclear distance. For alkali Rydberg atoms C_6 scales approximately as n^{11}, making the interaction strength dramatically tunable by selection of the Rydberg state. The van der Waals potential dominates at large interatomic separations and exhibits characteristic $1/R^6$ behavior that is fundamentally distinct from the resonant interactions at shorter range [26].

The resonant dipole-dipole interaction between two Rydberg atoms is given by the equation: $V_{dd}(R) = \pm \frac{C_3}{R^3}$. The C_3 coefficient relies on electronic states and the orientation of dipole moments. The $1/R^3$ dependency of this resonant effect becomes dominant on shorter interatomic distances, where the energies of coupled Rydberg pair states become nearly degenerate. There is a crossover distance (R_c) where dipole-dipole basically becomes similar to van der Waals. R_c will depend on both principle quantum number n and the Förster defect between paired state [26], where $R_c \approx (C_6 / C_3)^{1/3}$.

Theoretical and experimental works have designed in greater detail how such interactions can be engineered in scalable arrays of neutral atoms, and scaled the blockade radius with Floquet frequency modulation to scale qubit connectivity [1, 27]. Experimental and theoretical studies continue to expand on quantum simulation capabilities, using Rydberg blockade, dipole-dipole, and anti-blockade/facilitation effects to simulate condensed matter phenomena and optimize quantum logic device architectures [28]. These advancements collectively establish controlled dipole-dipole and van der Waals interactions as essential mechanisms for scalable entanglement synthesis and quantum simulation, thereby supporting the advancement of next-generation neutral-atom quantum technology.

4.2 EIT in Rydberg Atoms

Rydberg atoms' EIT has developed into a powerful tool for studying and controlling light-matter interactions at the quantum level, opening up previously unimaginable opportunities for implementing quantum information protocols. EIT in Rydberg atoms is a potent tool for quantum logic operations and gate implementations because it is sensitive to detuning and can be significantly impacted by long-range interactions [29]. Recent advancements in Rydberg-EIT in alkali atoms have significantly improved experimental control, sensitivity, and utility making it a crucial platform for photonic quantum technologies and quantum memories. In current Rydberg-EIT experiments, ladder-based three-level systems in rubidium and cesium vapors are tuned to the high-excited Rydberg state with the probe and control field tuned to very high precision using a microwave drive [30]. The power and tunability of Rydberg-EIT in the transmission window facilitate sophisticated quantum control. Quantum information protocols enhancing the calibration and manipulation of quantum systems by microwave spectroscopy and EIT measurements re-establishes probe absorption tuning [31]. Experiments also establish high photon-photon interactions and multi-photon quantum correlations, which drive high-fidelity single-photon transistors, optical switches, and memory devices, often due to limitations imposed on natural linewidths and laser powers [1]. Consequently, Rydberg-EIT continues to be an important part of scalable light-matter interfaces, bridging the gap between the concepts of quantum optics and real-world quantum computation and quantum communication.

5. Rydberg Blockade in QIP

The Rydberg blockade process is still one of the core and rapidly growing fields of quantum information science because it can offer strong and tunable interactions (interactions whose strength and range can be precisely controlled using external fields or laser parameters) between neutral atoms. Recent experimental studies demonstrate that Rydberg blockade, with atom-molecule pairs that can provide independent and enhanced control, as well as new entanglement schemes, offers the additional benefit of expanding the quantum processing toolbox beyond conventional atomic arrays [32].

New gate designs efficiently exploit Rydberg energy shifts to realize quantum gates that are free from blockade errors, operate on timescales comparable to or shorter than the blockade-induced interaction time, and achieve improved gate fidelity while conserving the advantages of blockade-mediated entanglement and quantum logics [33]. Experimental milestones in scaling neutral-atom quantum processors have been achieved, using Rydberg blockade and excitation-induced entanglement to create multi-qubit gates, Schrödinger cat states, and quantum optimization tasks [34].

New proposals introduce geometric quantum gates for controlled-phase operations bypassing Rydberg blockade effect's crosstalk and decoherence issues. These gates offer faster, more resource-efficient quantum control in neutral-atom arrays [35]. Microwave dressing of Rydberg states enhances blockade radius and interaction strength allowing effective blockade at lower principal quantum numbers and better control for quantum gate implementations [36]. The investigation of superatom-type collective excitations is furthering the progression of long-lifespan collective Rydberg states that have the potential of quantum memory, long-range entanglement, and generation of multi-qubit entanglements [37]. Taken together, these developments validate the Rydberg blockade as a multifaceted and essential mechanism, propelling advancements in scalable, high-fidelity quantum processors and unveiling new possibilities in entanglement creation, quantum memory, and hybrid quantum architectures.

6. Experimental Platforms with Alkali Metals

The alkali metals are essential in quantum information science as they are used in numerous small-scale warm-vapor cells and cold atom traps. Alkali metals like rubidium and cesium are crucial for QIP and simulation experiments with cold atom platforms using MOTs for controllable ensembles [13]. Optical tweezers enable single-atom addressability in large arrays, enabling high-fidelity quantum state preparation and gate implementation. Optical lattices provide periodic, stable, and high-density atom arrangements for simulating strongly correlated quantum materials and lattice gauge theories [38].

Warm alkali vapour cells provide a compact, chip-scale experimental platform for quantum memory and sensing applications, enabling room-temperature operation without complex systems. Recent developments are showing realistic applications in fiber-coupled and integrated photonics [39]. The interaction of laser-atoms in chip-scale devices with alkali vapors can be used to illustrate the universality of the laser-atom interactions on quantum platforms. Laser excitation and microwave manipulation play an important role in the control of alkali atom quantum state. High-fidelity Rydberg excitation by using two-photon processes and microwave fields has been implemented and applied to Multi-qubit gates and multi-qubit spectroscopy [30, 40, 41].

Cold atom traps, warm vapor cells, laser and microwave control techniques, and photon-atom coupling enhance scalability for quantum gates and entanglement protocols. These experimental approaches form the foundation for scalable quantum networks and next-generation computing platforms. Figure 2**,** depicts the key experimental platforms that facilitate the utilization of alkali Rydberg atoms as a solid basis for quantum information processing.

Fig. 2: Experimental platform for QIP.

7. QIP Schemes with Rydberg Atoms

The Rydberg atoms have emerged as potent systems on which complex QIP systems can be implemented due to their many coherence times and unrealistically amplified interactions. Quantum gates such as controlled-NOT and controlled-Z in a QIP scheme make use of Rydberg atoms. The effect of the Rydberg blockade allows preventing the simultaneous excitations and performing the entangling processes on a high-fidelity scale and in a short period of time. The latest protests indicate that the gate fidelities are in excess of 0.9995, which allows error-corrected quantum computation [2, 40]. In atomic ensembles, Rydberg EIT has been used to improve quantum memories, enabling quantum states of photons to be stored and recreated coherently. The experimental developments demonstrate good correlations, controllable transmission windows, and little noise [1, 42].

The Rydberg atoms enable effective generation of entanglements, photon emission and protocols of detecting the quantum network. Their great light-matter coupling facilitates the quantum frequency conversion of microwaves to optical waves and vice versa, facilitating the use of hybrid quantum networking [43]. Quantum systems are being added to the Rydberg atoms to form universal processors. Superconducting qubits, ultracold molecules, and photonic nanostructures are in the category of hybrid approaches. These platforms combine the advantages of both systems, making them suitable for strong state transfer and complex simulation [44, 45]. By connecting various platforms and opening the door to universal quantum technologies, these developments collectively establish Rydberg atoms as a fundamental component of scalable QIP.

7.1 Rydberg Sensing Applications

Rydberg sensors are very sensitive at microwave frequencies due to strong resonant transitions [46]. At 63 MHz they are sensitive to 0.96 mu V cm^{-1} $Hz^{-1/2}$ which is close to the theoretical sensitivity of RF dipole antennas. Prior studies indicate that with the further developments of sensing methods, the phase and frequency detectable is with a Doppler resolution smaller than 100 Hz, even in a field strength of several hundred nV cm^{-1} [47]. We are, therefore, already heading towards quantum-projection-noise-limited electromagnetic-wave sensors. This may have far-reaching consequences such as in radio astronomy, radar systems and meticulous metrology.

The Rydberg receivers have unique features that boost wireless communications. Detecting, demodulating, and down-converting by atom-field interactions means doing without bulky off-the-shelf units [48]. Rydberg sensors can be used as compact alternatives to antennas for radar applications [49]. Rydberg sensors are capable of measuring soil moisture through a satellite signal during remote sensing, meaning that they can be used in a wide range of applications [50].

Another breakthrough in the Rydberg electrometry has been the development of atomic superheterodyne receivers, which are more sensitive to the measurement of weak fields that are beyond the capabilities of other direct AT splitting techniques [47]. This is a method that employs a local oscillator microwave field to create an atomic mixer in order to be detected with optical heterodyne techniques. Jing et al. reported a sensitivity of 55 nV cm^{-1} $Hz^{-1/2}$ and a smallest detectable field of 780 p V cm^{-1} which was much better than the atomic electrometers in the past. Recent progress using laser-cooled atoms has reached sensitivities of 10.0 nV cm^{-1} $Hz^{-1/2}$, which is close to the standard quantum limit [51]. Superheterodyne technique enables phase-resolution detection, which is important in coherent communications and radar systems, to be characterized completely [52].

8. Applications of Alkali Atoms in Quantum Technologies

Alkali-based Rydberg platforms represent a flexible quantum technology that can be easily utilized to achieve efficient quantum communication, simulate many-body systems, and detect weak electromagnetic fields with high sensitivity. They also have a nonlinear optical response that makes it easy to produce single-photon sources and non-classical states of light. The role of Alkali atoms; Rubidium (Rb) and Cesium (Cs) in quantum technology is described in Table 1.

Table 1: The Role of Rb and Cs Atoms in Quantum Technologies

Atoms	Key advantages	Limitations	Applications	Ref.
Rb	The large dipole moments, lifetimes, and polarizability of Rydberg atoms increase their interactions and stability, which is why they are the best choice to use in quantum information systems and quantum gates in quantum computers.	The article explains the technical issues of handling Rydberg atoms in optical traps because they are sensitive to outside fields and forces and require sophisticated experimental technologies such as laser cooling and spectroscopy.	The article discusses cold rubidium Rydberg atoms as quantum computer qubits with their special characteristics in quantum information use.	[53]
Rb	A frequency comb for laser cooling efficiently cools neutral rubidium atoms near the Doppler limit. This method can scale to sub-Doppler temperatures by increasing comb intensity. This could replace traditional laser systems, enhance precision in quantum optics, and improve tests of fundamental physical constants and symmetries.	The cooling of neutral rubidium atoms is limited by the intensity of the comb mode, limiting cooling efficiency. To achieve sub-Doppler temperatures, the comb mode intensity must be increased by 40, indicating a low intensity regime and requiring comb power advancements.	The paper discusses the uses of laser cooling methods in atom interferometry, optical frequency standards and physics, and their possibilities to provide better tests, quantum degeneracy, and enhance ultracold chemistry and spectroscopy.	[54]
Rb	The peculiarities of an atom, such as Rydberg atoms are ready to be applied to scalable quantum technologies, such as quantum computing and the sensing of electromagnetic fields. They allow arrays of the same type of qubits, which are challenging to scale and connect, to be used, both to perform high-fidelity digital computation and analog quantum simulation.	Experiments with Rydberg atoms have low fidelity of entanglement generation with the largest published fidelity of 81%. It is because of the technical problems such as residual phase-noise and inherent gate errors. The higher methods such as Derivative Removal by Adiabatic Gate are required to obtain competitive gate speeds and fidelities.	The paper discusses the use of Rydberg atoms in quantum simulation and computing, particularly in optical tweezer arrays, for quantum algorithms and studying highly-correlated condensed-matter systems. It also highlights their application in sensing microwave and terahertz fields.	[55]
Rb	Cold Rydberg atoms have long lifetimes and strong dipole interactions, and can be used to perform quantum information and simulation technologies with Rydberg blockade. A quantum device and quantum networks are beneficial as integrating with optical waveguides consumes low energy and is highly scalable.	Rydberg atoms' excitation to higher principal quantum numbers is limited by ionization effects, especially for states with n greater than 68. This is due to their proximity to the optical nanofiber's dielectric surface and strong electric fields, which can shield the excitation process.	The paper explores the use of cold Rydberg atoms in quantum technologies, highlighting their potential for robust information devices when combined with optical waveguides, a crucial step towards all-fiber quantum networks.	[56]
Rb	The study presents an interferometric laser cooling method for ^{85}Rb atoms, reducing temperatures to 3 μK, offering a promising alternative to Doppler cooling for species without a closed radiative transition.	The interferometric laser cooling method's efficiency is limited by the time needed to accurately distinguish atom velocities, and spontaneous emission prevents it from increasing the phase space density of the atomic cloud.	The paper explores the use of interferometric laser cooling for sub-Doppler temperatures in atomic rubidium, a technique suitable for atomic physics experiments and suggests its extension to three-dimensional configurations.	[57]
Cs	Reduced stray fields enable high-resolution measurements. High sensitivity of Rydberg states for applications.	High sensitivity to electric and magnetic stray fields. Presence of ions can alter spectra line shapes.	Applications rely on high Rydberg states' sensitivity to environment. Dense Rydberg states generation and utilization are mentioned.	[58]
Cs	Accurate description of ultracold Rydberg gas interactions. Enables analysis of diverse Rydberg phenomena.	Reduced state selectivity in pulsed-field-ionization process. Background signal complicates millimeter-wave spectra analysis.	Formation of Rydberg macrodimers. Penning ionization in dense Rydberg gases. Rydberg-excitation-blockade effects.	[59]
Cs	Accurate Stark structure calculations for cesium atom. Good agreement between calculated and experimental results.	Parametric model potential slightly higher than Coulomb potential. Differences in phase conventions affect matrix element signs.	Stark structure calculations for cesium Rydberg atoms. Experimental observations in ultracold gas environments.	[60]
Cs	Enables high-precision measurements of isotopic shifts. Facilitates sensitive concentration ratio measurements in trace quantities.	High temperature required for efficient thermal desorption. Limited capture range for laser cooling mechanism.	High-precision measurements of isotopic and isomeric shifts. Sensitive measurements of isotopes' concentration ratios in trace quantities.	[61]
Cs	Highly tunable parameters and geometry for simulations. Precise control over interaction strengths in systems.	Effective Zeeman fields exceed interaction strengths. Rydberg state radiative lifetime limits experiment time.	Quantum information technology applications. Decoherence of a qubit over time.	[62]

Alkali atoms like potassium and sodium are also worthwhile options in quantum information technology owing to their advantageous atomic characteristics and availability. Their uncomplicated electronic configuration and clearly delineated transitions render them appropriate for investigating quantum protocols, photonics applications, and scalable systems. Although less mature than rubidium and cesium, their potential is considerable, as recent studies have emphasized benefits such as diminished collisional losses and alternative transition wavelengths that could enhance integration with nascent photonic technologies and scalable quantum systems [63, 64]. The role of Potassium (K) and Sodium (Na) in quantum information technology is pronounced in Table 2.

Table 2: The Role of Potassium (K) and Sodium (Na) Atoms in Quantum Technologies

Atoms	Key advantages	Limitations	Applications	Ref.
K	Collisional redistribution laser cooling enables efficient cooling of high-pressure atomic gases (e.g., potassium–argon), supporting low-temperature experiments. Efficiency may be enhanced with focused lasers, shorter absorption lengths, and heavier buffer gases.	The maximum temperature drop of 120 K from cooling is limited by argon gas thermal conductivity, affecting efficiency. The cooling efficiency in potassium-argon mixtures is lower than rubidium-argon mixtures due to faster line profile drop-off.	Future research may attain reduced temperatures through enhanced laser focusing and diminished absorption lengths, facilitating investigations of homogenous nucleation in saturated vapour.	[65]
K	The study provides recommendations for electric-dipole matrix elements and static polarizability of potassium atomic states, improving calculations and experimental setups in laser cooling and trapping applications, and enabling high phase-space density quantum gas.	The study explores potassium atom polarizability using a high-precision method, identifying 20 magic wavelengths for 4s 5p transitions. However, challenges like achieving phase-space density may limit accessibility for broader applications or simpler systems.	The study identifies magic wavelengths for potassium 4s np transitions, crucial for state-insensitive optical cooling and trapping, and producing a high phase-space density potassium quantum gas, advancing research in quantum physics and developing new technologies.	[66]
K	The multi-frequency laser system efficiently cools potassium atoms, trapping up to 4×109 41K atoms in 2.5 seconds. It produces a high-quality output beam, enabling sub-Doppler temperatures of 16 μK.	The system's low-power fiber-based telecom lasers may hinder scalability for larger applications, and the final free-space second-harmonic generation stage may introduce alignment and stability issues.	The multi-frequency laser system efficiently cools potassium (41K) atoms, trapping up to 4×109 atoms for ultracold atom physics experiments, offering fast loading times and sub-Doppler temperatures.	[67]
K	Improved accuracy in measuring Rydberg energy levels. Observation of a narrow transparency window under a strong probe field.	Sub-Doppler features vanish under weak-probe approximations. Inverted ladder types unfavorable for narrowing coherence window.	Sub-Doppler Rydberg spectroscopy of potassium atoms. Study of ground-state atom population decrease in traps.	[68]
K	The spectroscopic method uses Rydberg electrons' ponderomotive interaction to probe Rydberg-Rydberg transitions with reduced restriction, enhancing spatially-selective qubit manipulation in Rydberg-based quantum simulators and computers.	The method uses Rydberg electron ponderomotive interaction, but may limit probe types compared to electric-dipole couplings. Third and fourth-order sub-harmonic drives may introduce complexities and require precise optical phase modulator control, limiting scalability and practicality.	The method improves understanding and manipulation of Rydberg-Rydberg transitions through optical Doppler-free high-precision spectroscopy, enabling spatially-selective qubit manipulation with micrometer-scale resolution, crucial for Rydberg-based simulators and quantum computers.	[69]
Na	Direct cooling of Rydberg atoms enhances quantum simulation capabilities. Produces ultracold Rydberg atom clouds for temperature control.	Requires high I ($I \geq 10$) Rydberg states to prevent autoionization. Cooling dynamics complex due to residual Coulomb repulsion.	Direct laser cooling of Rydberg atoms proposed. Cooling dynamics with and without magnetic fields discussed.	[70]
Na	Robustness and beam quality of the laser source. High conversion efficiency and tunability over 60 GHz.	Temperature affects refractive indices and conversion efficiency. Requires careful optimization of cavity parameters for efficiency.	Atomic physics experiments with sodium atoms. Alternative to dye lasers for specific applications.	[71]
Na	Enhanced Rabi oscillations with $\sqrt{N}$ factor. Effective two-level model for quantum applications.	Rydberg states repelled by trapping laser fields. No enhancement for light shifts observed.	Quantum simulation using collective encoding in ensembles. Networking applications with trapped Rydberg qubits.	[72]
Na	Long intrinsic lifetimes enable extended trapping and observation. Flexible parameters allow diverse quantum simulations.	Analytic approaches to many-body systems are limited. Numerical simulations on classical computers are intractable.	Quantum phase transitions and transport studies. Study of thermalization, disorder, and Floquet time crystals.	[73]
Na	Achieves Doppler-free resolution of spectral structures. Investigates broadening and shift of transitions.	Requires lasers with narrow bandwidths for resolution. Broadening and shift affected by argon perturbation.	Observation of Rydberg states in sodium vapour. Achieving Doppler-free resolution of spectral structures.	[74]

9. Challenges and Future Prospects

Overcoming intrinsic decoherence and technical constraints that limit system performance are one of the main challenges in developing alkali-based quantum technologies. Intrinsic decoherence processes in alkali-based quantum platforms limit gate fidelity and memory lifetimes. Spontaneous emission, motional dephasing, and blackbody radiation-induced transitions lead to spectral broadening, coherence loss, and population leakage, necessitating sophisticated cooling or Doppler-free schemes [2, 75]. Laser stability is crucial for ultra-stable, narrow-linewidth lasers, but maintaining stability is complex and costly. Optimized optical and magnetic trap designs are needed for precise atom trapping, while high-resolution optics and beam control are needed for individual atoms [14, 20]. The gate fidelity and memory lifetimes deteriorate owing to intrinsic decoherence in alkali based quantum systems [76]. For alkali-based systems to achieve high-fidelity, long-lived quantum processes, these issues must be resolved.

A fundamental challenge in both trapped-ion and neutral-atom quantum computing is achieving scalable qubit architectures without sacrificing operational fidelity [77, 78]. For the case of trapped-ion systems, this requires low-cost and robust single-frequency lasers at application-specific wavelengths [78]. On the other hand, in the case of neutral atom systems, leakage errors emerge due to the quantum state escaping the computational subspace. The leakage may occur if the atom escapes the trapping potential, the atom is rendered unusable as it gets trapped in a metastable state, or if there are collisions with background gas. Furthermore, atom loss and atom heating during transport also render neutral atoms unviable for fault-tolerant quantum computers [79].

9.1 Error Correction and Fault-Tolerant Computing

Quantum error correction has become a foundation of designing scalable quantum computation, and various platforms, ranging from superconducting circuits to neutral atom arrays, have been designed with specific schemes to reduce decoherence and operational errors. The success of surface-code applications is an important milestone to fault-tolerant quantum computing, as it shows that it is possible to do realistic quantum error correction on superconducting systems. To address such special issues as the decay of Rydberg states, neutral atom arrays have been endowed with error correction protocols that are fault-tolerant to facilitate quantum computation [45]. Advanced hybrid systems for quantum error correction use nuclear spin qubits and optical clock qubits, using dual-isotope ytterbium atom arrays for data and ancilla qubits [80]. These advances indicate that superconducting and neutral-atom platforms are converging on effective error correction, establishing them as prime candidates for achieving scaled and fault-tolerant quantum computing.

9.2 Exploring Alternative Alkali Metals

The choice of alkali species and the disposal of the alkali species with photonic platforms are significant determinants of the efficiency and scalability of quantum technologies. Rubidium and cesium are the key players in laser technology, and potassium and sodium have been investigated to have benefits in silicon photonics and telecom technology, but their state of immaturity has restricted usage in quantum protocols [63, 64]. Hybrid architectures combining cold alkali atoms with photonic integrated circuits offer scalable photon-atom interfaces, enabling strong light confinement and enhanced atom-photon coupling for quantum repeaters, interconnects, and distributed quantum computation [81]. Finding the best alkali options and developing scalable quantum architectures will depend heavily on these hybrid integrations and comparative investigations.

Conclusion

Alkali atoms, particularly rubidium and cesium, are crucial for quantum information processing due to their accessibility, long coherence times, and compatibility with advanced trapping and control techniques. Mechanisms like EIT, dipole-dipole interactions, and Rydberg blockade enable high-fidelity quantum gates, scalable quantum memories, and entanglement-based communication protocols. The integration of optical tweezers, lattices, and warm vapor cells has expanded the experimental landscape. Despite challenges like decoherence and laser stability, rapid progress highlights the adaptability of alkali-based systems. Advances in coherence preservation, error correction, and nanophotonics will drive alkali Rydberg platforms closer to fault-tolerant quantum computing and quantum simulation.

Deceleration of Competing Interest:

Author declares no conflict of interest in this study and no other journal has previously published this article.

Acknowledgement: None

Source of Funding: None

References

[1] S. Xiao-Qiang, S. Shi-Lei, L. Lin, R. Nath, J. H. Wu, and W. Li, “Rydberg superatoms: An artificial quantum system for quantum information processing and quantum optics,” Appl. Phys. Rev., vol. 11, no. 3, p. 031320, 2024.

[2] M. Xue, S. Xu, X. Li, and X. Liang, “High-fidelity and robust controlled-Z gates implemented with Rydberg atoms via echoing rapid adiabatic passage,” Phys. Rev. A, vol. 110, no. 3, p. 032619, 2024.

[3] K. Singh, S. Anand, A. Pocklington, J. T. Kemp, and H. Bernien, “Dual-Element, Two-Dimensional Atom Array with Continuous-Mode Operation,” Phys. Rev. X, vol. 12, no. 1, p. 011040, 2022.

[4] E. Gómez-López, K. Winkler, J. Jurkat, M. Meinecke, J. Wolters, T. Huber-Loyola, S. Höfling, O. Benson, D. F. Figer, and M. Reimer, “Atomic vapor quantum memory for on-demand semiconductor single photon sources,” in Proc. Photonics for Quantum 2023, Rochester, NY, USA, Jun. 5–8, 2023, pp. 14–23, SPIE, 2023.

[5] P. M. Burdekin, I. Maillette de Buy Wenniger, S. Sagona-Stophel, J. Szuniewicz, A. Zhang, S. E. Thomas, and I. A. Walmsley, “Enhancing quantum memories with light-matter interference,” arXiv preprint arXiv: 2411.17365, 2024.

[6] H. B. Zhang, Y. Tang, and Y. C. Liu, “Nuclear spin induced transparency,” Phys. Rev. Research, vol. 7, no. 1, p. L012069, 2025.

[7] M. Saffman, T. G. Walker, and K. Mølmer, “Quantum information with Rydberg atoms,” Rev. Mod. Phys., vol. 82, no. 3, pp. 2313–2363, 2010.

[8] T. Chen, X. Li, F. Zhang, L. Wang, and Y. Zhao, “Quantum walks and correlated dynamics in an interacting synthetic Rydberg lattice,” Phys. Rev. Lett., vol. 133, no. 12, p. 120604, 2024.

[9] N. Reinić, S. Müller, D. Schuster, E. Kovacs, and M. Lang, “Finite-temperature Rydberg arrays: Quantum phases and entanglement characterization,” Phys. Rev. Research, vol. 6, no. 3, p. 033322, 2024.

[10] L. Homeier, M. Chen, J. Fischer, and P. Klein, “Supersolidity in Rydberg tweezer arrays,” Phys. Rev. A, vol. 111, no. 1, p. L011305, 2025.

[11] M. Norcia, L. Zhang, S. Ivanov, and T. Keller, “Iterative assembly of 171 Yb atom arrays with cavity-enhanced optical lattices,” PRX Quantum, vol. 5, no. 3, p. 030316, 2024.

[12] P. N. T. Lloyd and R. Bekenstein, "Single atomic layer quantum holography," Phys. Rev. Research, vol. 7, no. 2, p. L022014, 2025.

[13] L. Yang et al., "Rapid preparation of Rydberg superatom W state using superadiabatic techniques," Acta Phys. Sin., vol. 74, no. 10, pp. 100305-1–100305-9, 2025.

[14] A. Bhowmik and D. Blume, "Forces on alkali Rydberg atoms due to nonlinearly polarized light," Phys. Rev. A, vol. 111, no. 5, p. 053120, 2025.

[15] H. J. Manetsch, L. Müller, D. Kim, and E. Rossi, "A tweezer array with 6100 highly coherent atomic qubits," arXiv preprint arXiv: 2403. 12021, 2024.

[16] A. Holman et al., "Trapping of single atoms in metasurface optical tweezer arrays," arXiv preprint arXiv: 2411.05321, 2024.

[17] Y. Torii Chew et al., "Ultra-precise holographic optical tweezers array," arXiv preprint arXiv: 2407.20699, 2024.

[18] T. Steckmann et al., "Error mitigation of shot-to-shot fluctuations in analog quantum simulators," arXiv preprint arXiv: 2506.16509, 2025.

[19] S. G. Menon et al., "An integrated atom array-nanophotonic chip platform with background-free imaging," Nat. Commun., vol. 15, no. 1, p. 6156, 2024.

[20] J. Sinclair et al., "Fault-tolerant optical interconnects for neutral-atom arrays," Phys. Rev. Research, vol. 7, no. 1, p. 013313, 2025.

[21] G. Higgins et al., "Single strontium Rydberg ion confined in a Paul trap," Phys. Rev. X, vol. 7, no. 2, p. 021038, 2017.

[22] B. Hezel, M. Mayle, and P. Schmelcher, "Interaction-induced stabilization of circular Rydberg atoms," Phys. Rev. A, vol. 84, no. 6, p. 063402, 2011.

[23] S. Anand et al., "A dual-species Rydberg array," Nat. Phys., vol. 20, no. 11, pp. 1744–1750, 2024.

[24] V. Crescimanna et al., "Quantum control of Rydberg atoms for mesoscopic quantum state and circuit preparation," Phys. Rev. Appl., vol. 20, no. 3, p. 034019, 2023.

[25] F. Cesa and H. Pichler, "Universal quantum computation in globally driven Rydberg atom arrays," Phys. Rev. Lett., vol. 131, no. 17, p. 170601, 2023.

[26] M. Londoño et al., "Ultracold long-range van der Waals Rydberg trimer," Commun. Phys., vol. 8, p. 232, 2025.

[27] G. Giudici et al., "Fast entangling gates for Rydberg atoms via resonant dipole-dipole interaction," PRX Quantum, vol. 6, no. 3, p. 030308, 2025.

[28] J. Kumlin et al., "Quantum optics with Rydberg superatoms," J. Phys. Commun., vol. 7, no. 5, p. 052001, 2023.

[29] M. Rashid, H. Maarten, and J. Yasir, "C-NOT gate based on ultracold Rydberg atom interactions," Sci. China Phys. Mech. Astron., vol. 56, no. 11, pp. 2134–2137, 2013.

[30] E. Brekke and C. Umland, "Rydberg excitation through detuned microwave transition in rubidium," J. Opt. Soc. Am. B, vol. 40, no. 11, pp. 2758–2761, 2023.

[31] N. D. Gomes et al., "Microwave spectroscopy assisted by electromagnetically induced transparency near natural Förster resonance on rubidium," Results Phys., vol. 68, p. 108081, 2025.

[32] H. Shen and J. Zhang, "Entanglement-enhanced quantum metrology with neutral atom arrays," Natl. Sci. Rev., vol. 12, no. 8, pp. 1–3, 2025.

[33] X.-F. Shi, "Rydberg quantum gates free from blockade error," Phys. Rev. Appl., vol. 7, no. 6, Art. no. 064017, Jun. 2017.

[34] S. K. Barik et al., "Quantum technologies with Rydberg atoms," Front. Quantum Sci. Technol., vol. 3, Art. no. 1426216, pp. 1–6, 2024.

[35] Y. Ming, Z.-X. Fu, and Y.-X. Du, "New-type geometric gates in atomic arrays without Rydberg blockade," arXiv preprint arXiv: 2412.19193, 2024.

[36] D. Kurdak et al., "Enhancement of Rydberg blockade via microwave dressing," Phys. Rev. Lett., vol. 134, no. 12, p. 123404, 2025.

[37] Z.-Y. An et al., "Entangling two Rydberg superatoms via heralded storage," Phys. Rev. Lett., vol. 134, no. 23, p. 230803, 2025.

[38] C. Apostoli et al., "Unraveling open quantum dynamics with time-dependent variational Monte Carlo," arXiv preprint arXiv: 2506.23928, 2025.

[39] E. Butery et al., "Sub-Doppler spectroscopy of Rydberg atoms via velocity selection memory in a hot vapor cell," Opt. Lett., vol. 50, no. 2, pp. 578–581, 2025.

[40] S. Xu et al., "Efficient generation of multiqubit entanglement states using rapid adiabatic passage," Phys. Rev. A, vol. 110, no. 2, p. 023108, 2024.

[41] T. Firdoshi et al., Six-wave mixing of optical and microwave fields using Rydberg excitations in thermal atomic vapor. arXiv preprint arXiv:2207.01835, 2022.

[42] Y. Liang et al., "Cavity-enhanced Rydberg atomic superheterodyne receiver," Opt. Express, vol. 33, no. 6, pp. 13034–13039, 2025.

[43] K. Mukherjee et al., "Automated quantum system modeling with machine learning," Quantum Sci. Technol., vol. 10, no. 2, p. 02LT01, 2025.

[44] K. Wang et al., "Enriching the quantum toolbox of ultracold molecules with Rydberg atoms," PRX Quantum, vol. 3, no. 3, p. 030339, 2022.

[45] I. Cong et al., "Hardware-efficient, fault-tolerant quantum computation with Rydberg atoms," Phys. Rev. X, vol. 12, no. 2, p. 021049, 2022.

[46] W. Yang et al., "RF E-field enhanced sensing based on Rydberg-atom-based superheterodyne receiver," arXiv preprint arXiv:2401.01663, 2024.

[47] M. Jing et al., "Atomic superheterodyne receiver based on microwave-dressed Rydberg spectroscopy," Nat. Phys., vol. 16, no. 9, pp. 911–915, 2020.

[48] T. Gong et al., "Rydberg atomic quantum receivers for classical wireless communication and sensing," IEEE Wireless Commun., vol. 32, no. 5, pp. 90–100, 2025.

[49] D. H. Meyer et al., "Digital communication with Rydberg atoms and amplitude-modulated microwave fields," Appl. Phys. Lett., vol. 112, no. 21, p. 211108, 2018.

[50] S. Borówka et al., "Rydberg-atom-based system for benchmarking millimeter-wave automotive radar chips," Phys. Rev. Appl., vol. 22, no. 3, p. 034067, 2024.

[51] H.-T. Tu et al., "Approaching the standard quantum limit of a Rydberg-atom microwave electrometer," Science Adv., vol. 10, no. 51, p. eads0683, 2024.

[52] S. Berweger et al., "Closed-loop quantum interferometry for phase-resolved Rydberg-atom field sensing," Phys. Rev. Appl., vol. 20, no. 5, p. 054009, 2023.

[53] I. I. Ryabtsev et al., "Spectroscopy of cold rubidium Rydberg atoms for applications in quantum information," Phys.-Usp., vol. 59, no. 2, p. 196, 2016.

[54] N. Šantić et al., "Cooling of atoms using an optical frequency comb," Sci. Rep., vol. 9, no. 1, p. 2510, 2019.

[55] C. S. Adams, J. D. Pritchard, and J. P. Shaffer, "Rydberg atom quantum technologies," J. Phys. B: At. Mol. Opt. Phys., vol. 53, no. 1, p. 012002, 2019.

[56] A. Vylegzhanin et al., "Excitation of 87Rb Rydberg atoms to n S and n D states (n ≤ 68) via an optical nanofiber," Optica Quantum, vol. 1, no. 1, pp. 6–13, 2023.

[57] A. Dunning et al., "Interferometric laser cooling of atomic rubidium," Phys. Rev. Lett., vol. 115, no. 7, p. 073004, 2015.

[58] H. Sabmannshausen, Frédéric Merkt, and Johannes Deiglmayr, "High-resolution spectroscopy of Rydberg states in an ultracold cesium gas," Phys. Rev. A, vol. 87, no. 3, p. 032519, 2013.

[59] H. Sabmannshausen, Frédéric Merkt, and Johannes Deiglmayr, "Pulsed excitation of Rydberg-atom-pair states in an ultracold Cs gas," Phys. Rev. A, vol. 92, no. 3, p. 032505, 2015.

[60] C. Li, X. Zhang, Y. Wang, and H. Chen, "Numerically calculated Stark structures of cesium Rydberg atom and experimental observation in an ultracold gas," J. Phys. Soc. Jpn., vol. 81, no. 4, p. 044302, 2012.

[61] A. Giatzoglou, M. Papadopoulos, E. Karydas, and S. Economou, "A facility for production and laser cooling of cesium isotopes and

isomers," Nucl. Instrum. Methods Phys. Res. Sect. A, vol. 908, pp. 367–375, 2018.

[62] J. Dobrzyniecki and M. Tomza, "Quantum simulation of the central spin model with a Rydberg atom and polar molecules in optical tweezers," Phys. Rev. A, vol. 108, no. 5, Art. no. 052618, pp. 1–23, 2023.

[63] A. Laskowski and N. P. Mehta, "Homonuclear ultracold elastic s-wave collisions of alkali-metal atoms via multichannel quantum defect theory," Phys. Rev. A, vol. 108, no. 4, p. 043306, 2023.

[64] H. Suno, T. Yamamoto, M. Kobayashi, and Y. Nakamura, "Quantum chemical calculation studies toward microscopic understanding of retention mechanism of Cs radioisotopes and other alkali metals in lichens," Sci. Rep., vol. 11, no. 1, p. 8228, 2021.

[65] A. Sab, U. Vogl, and M. Weitz, "Laser cooling of a potassium–argon gas mixture using collisional redistribution of radiation," Appl. Phys. B, vol. 102, no. 3, pp. 503–507, 2011.

[66] M. Safronova, U. I. Safronova, and C. W. Clark, "Laser cooling and trapping of potassium at magic wavelengths," arXiv preprint arXiv: 1301.3181, 2013.

[67] C. Cherfan, L. Dupont, A. Martin, and P. Lefevre, "Multi-frequency telecom fibered laser system for potassium laser cooling," Appl. Phys. Lett., vol. 119, no. 20, p. 204001, 2021.

[68] T.L. Chen, Y. H. Li, W. Zhang, and H. Xu, "Inverted-ladder-type optical excitation of potassium Rydberg states with hot and cold ensembles," Phys. Rev. A, vol. 101, no. 5, p. 052507, 2020.

[69] R. Cardman and G. Raithel, "Driving alkali Rydberg transitions with a phase-modulated optical lattice," Phys. Rev. Lett., vol. 131, no. 2, p 023201, 2023.

[70] A. Bouillon, E. M. Bujedo, and M. Génévriez, "Direct laser cooling of Rydberg atoms with an isolated-core transition," Phys. Rev. Lett., vol. 132, no. 19, p. 193402, 2024.

[71] E. Mimoun, C. Dubois, and F. Lambert, "Solid-state laser system for laser cooling of sodium," Appl. Phys. B, vol. 99, no. 1, pp. 31–40, 2010.

[72] Y. Mei, L. Chen, X. Zhang, and R. Wang, "Trapped alkali-metal Rydberg qubit," Phys. Rev. Lett., vol. 128, no. 12, p. 123601, 2022.

[73] T.L. Nguyen, A. Dupont, and S. Martin, "Towards quantum simulation with circular Rydberg atoms," Phys. Rev. X, vol. 8, no. 1, p. 011032, 2018.

[74] W. Yan-Bang, L. Ming, and Z. Qiang, "Observation of Rydberg series in sodium vapour by two-photon resonant nondegenerate four-wave mixing," Chin. Phys. Lett., vol. 18, no. 9, pp. 1202–1204, 2001.

[75] D. B. Branden, E. R. Smith, and T. J. Wilson, "Radiative lifetime measurements of rubidium Rydberg states," J. Phys. B: At. Mol. Opt. Phys., vol. 43, no. 1, p. 015002, 2009.

[76] A. Dalal and B. C. Sanders, "Two-qubit gate in neutral atoms using transitionless quantum driving," Phys. Rev. A, vol. 107, no. 1, p. 012605, 2023.

[77] R. Mitsch, C. Sayrin, B. Albrecht, P. Schneeweiss, and A. Rauschenbeutel, "Quantum state-controlled directional spontaneous emission of photons into a nanophotonic waveguide," Nat. Commun., vol. 5, no. 1, p. 5713, 2014.

[78] K. Nechay, A. Ivanov, L. Schmidt, and M. Becker, "Multiwavelength narrow linewidth laser system for Ba^+ quantum computing applications," in Quantum Computing, Communication, and Simulation IV, vol. 12911, SPIE, pp. 337–342, 2024.

[79] S. Omanakuttan, R. Verma, L. Zhao, and M. Krüger, "Coherence preserving leakage detection and cooling in alkaline earth atoms," arXiv preprint arXiv: 2410.23430, 2024.

[80] Y. Nakamura, H. Saito, K. Tanaka, and M. Kobayashi, "Hybrid atom tweezer array of nuclear spin and optical clock qubits," Phys. Rev. X, vol. 14, no. 4, p. 041062, 2024.

[81] S. G. Menon, L. Chen, A. Martinez, and H. Tanaka, "Nanophotonic quantum network node with neutral atoms and an integrated telecom interface," New J. Phys., vol. 22, no. 7, p. 073033, 2020.