TOWARDS QUANTUM MEMORY USING LASER COOLED CESIUM ATOMS

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Towards Quantum Memory using Laser Cooled Cesium Atoms

by

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I dedicate this thesis to my parents and family!

CERTIFICATE

This is to certify that the thesis titled **"Towards Quantum Memory using Laser Cooled Cesium Atoms"**, submitted by **Ms. Poonam Yadav** to the Department of Physics, Indian Institute of Technology Delhi, in partial fulfillment of the requirements for the degree of Doctor of Philosophy, is based on original research conducted under my supervision.

To the best of our knowledge, the work presented meets the standards expected for a doctoral thesis. The results and findings reported herein have not been submitted, either in part or full, to any other university or institution for the award of a degree or diploma.

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Abstract

Quantum memory is an essential unit for enabling light–matter interaction in quantum communication network and quantum computing. It allows to store quantum information for a desired duration and retrieval on demand. Light possess multiple degrees of freedom, which can be mapped onto atomic states and later retrieved as photonic states on demand. A suitable physical platform is required to serve as the memory medium and a well-defined atomic interaction energy levels scheme for the storage of quantum states. Cold atoms offer a highly controlled, isolated environment, and facilitating strong light–matter interactions at high optical depths and low temperature in a few microkelvin range.

In this thesis, we study an electromagnetically induced transparency (EIT) in cesium D2 line using a Λ-type configuration of atomic energy levels. Firstly, we demonstrate slow light propagation in room-temperature cesium vapor using EIT lineshape measurements. We show that the narrow spectral width of the EIT resonance enables slow light propagation of a weak signal field in the presence of a strong control field.

Decoherence is the main source that limits the coherence of quantum states in light matter interactions. We measure the decoherence rate using accurate lineshape spectroscopy involving hyperfine ground states of D2 transition of ^{133}Cs atoms in warm vapor at room temperature.

We then theoretically examined the storage efficiency, fidelity and lifetime of an EIT-based quantum memory considering an ensemble of cold cesium atoms. We demonstrated that high efficiency and storage time of pulses can be achieved at very low temperature and in a highly optically dense medium.

We have reported the laser-cooled ensemble of cesium atoms using magneto optical trap (MOT) and obtained temperature of 11 ± 0.64 μK after polarization gradient cooling and trapped atoms millions of cesium atoms. The significantly reduced temperature helps to suppress decoherence and thus improves the fidelity of quantum state storage. In addition, we implemented offset locking techniques to mitigate decoherence arising from EIT lasers frequency instabilities.

Furthermore, we investigated loss-assisted collisions arising from background gas atoms and inter-particle interactions within the cold atoms cloud. We also reported the fidelity of state-selective detection, which is essential for accurate quantum state readout.

सार

क्वांटम संचार नेटवर्क और क्वांटम कंप्यूटिंग में प्रकाश-पदार्थ अंतःक्रिया को सक्षम करने के लिए क्वांटम मेमोरी एक आवश्यक इकाई है। यह क्वांटम सूचना को वांछित अवधि तक संग्रहीत करने और माँग पर पुनः प्राप्त करने की अनुमति देती है। फोटॉन में स्वतंत्रता की कई कोटि होती हैं, जिन्हें परमाणु अवस्थाओं पर चित्रित किया जा सकता है और बाद में माँग पर फोटोनिक अवस्थाओं के रूप में पुनः प्राप्त किया जा सकता है। क्वांटम अवस्थाओं के भंडारण के लिए एक सुपरिभाषित परमाणु अंतःक्रिया ऊर्जा स्तर योजना के रूप में कार्य करने के लिए एक उपयुक्त भौतिक आधार मंच की आवश्यकता होती है। ठंडे परमाणु एक अत्यधिक नियंत्रित, पृथक वातावरण प्रदान करते हैं, और कुछ माइक्रोकेल्विन तापमान रेंज में उच्च प्रकाशीय गहराई और कम तापमान पर प्रबल प्रकाश-पदार्थ अंतःक्रियाओं को सुगम बनाते हैं।
इस शोध प्रबंध में, हम परमाणु ऊर्जा स्तरों के Λ-प्रकार के विन्यास का उपयोग करके सीज़ियम परमाणु की D2 ऊर्जा स्तर में विद्युतचुंबकीय प्रेरित पारदर्शिता (EIT) का अध्ययन करते हैं। सबसे पहले, हम EIT स्पेक्ट्रोस्कोपिक रेखारूप मापों का उपयोग करके कमरे के तापमान वाले सीज़ियम वाष्प में धीमी प्रकाश संचरण का प्रदर्शन करते हैं। हम दर्शाते हैं कि EIT अनुनाद की संकीर्ण वर्णक्रमीय चौड़ाई एक प्रबल नियंत्रण क्षेत्र की उपस्थिति में एक दुर्बल संकेत क्षेत्र के धीमे प्रकाश संचरण को सक्षम बनाती है। विसंबद्धता वह मुख्य स्रोत है जो प्रकाश पदार्थ अंतःक्रियाओं में क्वांटम अवस्थाओं की सुसंगतता को सीमित करता है। हम सटीक रेखा-आकार स्पेक्ट्रोस्कोपी का उपयोग करके विसंबद्धता दर को मापते हैं, जिसमें कमरे के तापमान पर गर्म वाष्प में ^{133}Cs परमाणुओं के D2 संक्रमण की अतिसूक्ष्म मूल अवस्थाएँ शामिल हैं।

फिर हमने सैद्धांतिक रूप से एक EIT-आधारित क्वांटम मेमोरी की भंडारण क्षमता, सत्यता और संग्रहण समय की जाँच की, जिसमें ठंडे सीज़ियम परमाणुओं का एक समूह शामिल था। हमने प्रदर्शित किया कि उच्च क्षमता और स्पंदों का भंडारण समय बहुत कम तापमान पर और अत्यधिक प्रकाशिक रूप से सघन माध्यम में प्राप्त किया जा सकता है।

हमने चुंबकीय-प्रकाशीय जाल का उपयोग करके सीज़ियम परमाणुओं के लेज़र-शीतित समूह की प्रतिवेदन की है और ध्रुवीकरण ढाल शीतलन से लाखों फंसे हुए सीज़ियम परमाणुओं के लिए हमने $11 \pm 0.64\ \mu K$ का तापमान प्राप्त किया है। उल्लेखनीय रूप से कम तापमान विसंयोजन को दबाने में मदद करता है और इस प्रकार क्वांटम अवस्था भंडारण की विश्वसनीयता में सुधार करता है।

इसके अलावा, हमने EIT लेज़र किरणों की आवृत्ति अस्थिरताओं से उत्पन्न विसंयोजन को कम करने के लिए अंतर लॉकिंग तकनीकों को लागू किया। इसके अतिरिक्त, हमने पृष्ठभूमि गैस परमाणुओं और ठंडे परमाणु बादल के भीतर अंतर-कण अंतःक्रियाओं से उत्पन्न होने वाली हानि-सहायता प्राप्त टक्करों की जाँच की।

अंत में, हमने अवस्था-चयनात्मक संसूचन की विश्वसनीयता की भी रिपोर्ट की, जो सटीक क्वांटम अवस्था प्राप्त जानकारी के लिए आवश्यक है।

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Constants and notations:

The following standard physical constants will be used:

- Speed of Light in vacuum c = 2.99792458×10^{8} m/s
- Planck constant h = 6.626×10^{-34} J s
- Reduced Planck constant $\hbar = 1.054 \times 10^{-34}$ J s
- Boltzmann constant $k_B = 1.380649 \times 10^{-23}\ \mathrm{J\,K^{-1}}$
- Bohr magneton $\mu_B = 9.27401584 \times 10^{-24}\ \mathrm{J\,T^{-1}}$
- Atomic mass unit (1 amu) = $1.66053906892 \times 10^{-27}$ kg
- Vacuum permittivity $\epsilon_0 = 8.854187817620 \times 10^{-12}\ \mathrm{F\,m^{-1}}$
- Vacuum permeability $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{H\,m^{-1}}$
- Bohr radius $a_0 = 0.52917720859(36) \times 10^{-10}$ m
- Elementary charge $e = 1.602176487(40) \times 10^{-19}$ C
- Elementary mass $e = 9.10938356(28) \times 10^{-31}$ kg
- $\pi = 3.1415926535$

FWHM: Full width half maximum,
PD: Photo detector,
CMOS: Complementary Metal-Oxide-Semiconductor,
ECDL: External cavity diode laser,
MOF: Mode of free range,
SAS: saturated absorption spectroscopy,
FMS: Frequency modulations spectroscopy,
DAVLL: Dichroic atomic vapor laser locking,
PBS: Polarization beam splitter,
HWP: Half wave plate,
QWP: Quarter wave plate,
AOM: Acousto optic modulator,
MOT: Magneto optical trap,
PCG: Polarization gradient cooling,
EIT: Electromagnetically induced transparency,
DSP: Dark state polariton,
VSP: Velocity selective optical pumping,

ATS: Autler-Townes splitting,
D: Optical depth,
SA: Solid angle,
FPS: Frames per seconds,
FPGA: Field programmable gate array,
DAQ: Data acquisition system,
MOSFET: Metal-Oxide-Semiconductor Field-Effect Transistor,
UHV: Ultra high vacuum,
k: Wavevector,
σ^+, σ^-: Right handed and left handed circularly polarized light,
λ: Optical wavelength,
Ω: Rabi frequency,
Γ: Natural linewidth of $6\,^2S_{1/2} \rightarrow 6\,^2P_{3/2}$ (D2 line) of ^{133}Cs atom,
η : Quantum memory efficiency,
τ_d : Storage time of light pulse in medium,
R_{sc}: Photon scattering rate,
I: Laser beam intensity,
I_{sat}: Saturation intensity,
Ω_p: Signal field Rabi frequency,
Ω_c: Control file Rabi frequency,
v_g: Signal field group velocity in EIT medium,
L: Length of atomic medium,
γ_{EIT}: EIT linewidth,
B: Magnetic field,
E: Electric field,