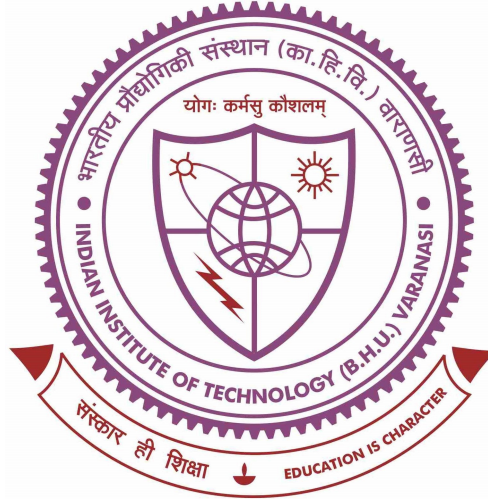


Exploring Exotic Phenomena in Hybrid Quantum Systems



Thesis submitted in partial fulfillment for
The Award of Degree

Doctor of Philosophy
in
Physics

by

Kuldeep Kumar Shrivastava

DEPARTMENT OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY
(BANARAS HINDU UNIVERSITY)
VARANASI - 221005

Roll No. 18171007

2024

**Dedicated to
the unrecognized soldiers of
the Indian Armed Forces
and their families who gave it all away
for the sake of their nation.**

“No amount of money or success can take the place of time spent with your family”



भारतीय
प्रौद्योगिकी
संस्थान
काशी हिन्दू विश्वविद्यालय



INDIAN
INSTITUTE OF
TECHNOLOGY
BANARAS HINDU UNIVERSITY

CERTIFICATE

It is certified that the work contained in the thesis titled “Exploring Exotic Phenomena in Hybrid Quantum Systems” by “Kuldeep Kumar Shrivastava” has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive Examination, Candidacy and SOTA for the award of Ph.D. Degree.

Rajeev Singh
29/08/24

Signature of the Supervisor

Dr. Rajeev Singh
(Assistant Professor)
Department of Physics
Indian Institute of Technology
(Banaras Hindu University)
Varanasi-221005 (U.P), India

Assistant Professor
Department of Physics
Indian Institute of Technology
(Banaras Hindu University)
Varanasi-221005



भारतीय
प्रौद्योगिकी
संस्थान
काशी हिन्दू विश्वविद्यालय

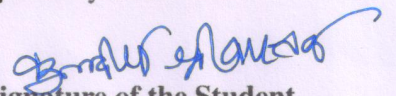


INDIAN
INSTITUTE OF
TECHNOLOGY
BANARAS HINDU UNIVERSITY

DECLARATION BY THE CANDIDATE

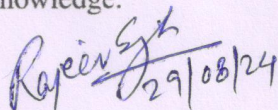
I, "Kuldeep Kumar Shrivastava", certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of "Dr. Rajeev Singh" from August, 2018 to July, 2024, at the "Department of Physics", Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, etc., reported in journals, books, magazines, reports dissertations, theses, etc., or available at websites and have not included them in this thesis and have not cited as my own work.

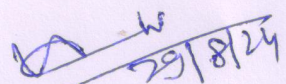
Date : 29/08/2024
Place: IIT (BHU), Varanasi


Signature of the Student
(Kuldeep Kumar Shrivastava)

CERTIFICATE BY THE SUPERVISOR

It is certified that the above statement made by the student is correct to the best of my knowledge.


Supervisor
Dr. Rajeev Singh
(Assistant Professor)
Assistant Professor
Department of Physics
Indian Institute of Technology
(Banaras Hindu University)
Varanasi-221005


Signature of Head of Department
Prof. Sandip Chatterjee
HEAD/विभागाध्यक्ष
भौतिकी विभाग/Dept. of Physics
भा०प्रौ०सं०/(का०हि०वि०)/IIT (BHU)
वाराणसी/Varanasi-221005



भारतीय
प्रौद्योगिकी
संस्थान
काशी हिन्दू विश्वविद्यालय



INDIAN
INSTITUTE OF
TECHNOLOGY
BANARAS HINDU UNIVERSITY

COPYRIGHT TRANSFER CERTIFICATE

Title of the Thesis : Exploring Exotic Phenomena in Hybrid Quantum Systems

Name of the Student : Kuldeep Kumar Shrivastava

Copyright Transfer

The undersigned hereby assigns to the Institute of Technology (Banaras Hindu University) Varanasi all rights under copyright that may exist in and for the above thesis submitted for the award of the “Doctor of Philosophy”.

Date : 29/08/2024

Place: IIT (BHU), Varanasi

Signature of the Student
(Kuldeep Kumar Shrivastava)

Note: However, the author may reproduce or authorize others to reproduce material extracted verbatim from the thesis or derivative of the thesis for the author’s personal use provided that the source and the Institute’s copyright notice are indicated.

ACKNOWLEDGEMENTS

Foremost, I express my deep sense of gratitude to my research supervisor, Dr. Rajeev Singh, for his excellent guidance, motivation, and constant encouragement throughout my entire research work. The insightful discussions with him have always provided me with great enthusiasm. I am extremely thankful to the Head of the Department, my RPEC members, Dr. Sanjay Singh (SMST) and Dr. Sunil Kumar Mishra, for their numerous insightful suggestions during the entire course of this research. I am also grateful to Dr. Biswanath Bhoi (IIT-BHU) and Dr. Dibyendu Roy (RRI Bangalore) for their valuable support through insightful discussions. I take this opportunity to express my gratefulness to all the faculty members of the Department of Physics for their kind encouragement and motivation throughout my research period. I am also thankful to the entire non-teaching staff of the Department for their support.

I wish to thank my lab companions and friends—Abhishek Maurya, Ekta Tunwal, Rakesh Kumar Nayak, Sachin Verma, Ansuman Sahu (IISER Berhampur), Prashant Choudhary, Manjushree Maity, Sanjeev Gupta, Meghana Mishra, Shubham Singh, Moulik Deviprasad Ketkar, and all lab members of the "Nano-Magnetism and Quantum Technology Lab, Department of Physics, IIT (BHU)"—for providing me with a conducive environment to carry out my research. I would also like to express my sincere appreciation to my colleagues and friends, Seema Kumari, Manisha (Monia Dixit), Tushar Sarkar, Ankita Chowdhury, Vindya Vashishth, Arpita, Sanjeet Patel, Sanjeev Sanyal, Prem Chand Bharti, Satya Vijay, Dheeraj, and all research scholars of the department for their lively friendship and support at all stages of my research.

I find myself at a loss for words to fully express my deep appreciation, gratitude, and indebtedness to my father, Shri Shambhu Prasad Shrivastava, and my mother, Smt. Rekha Devi; to my brother, Ranjeet Kumar; and to my beloved Nisha, Ronika, and all family members. I am also profoundly grateful to Madnagar, Vijay ji, Shikha Singh Sengar, Navanit, Lalita and Anita didi (my beloved twin sisters), Harikrishna Mishra, Abhishek Maurya, Vivekananda (Swami), Balmukund Ji, and the entire family. Their unbounded love, blessings, encouragement, and unwavering support have been the foundation of my academic journey.

I am truly blessed to feel the divine presence of some of the most conscious and eternally great individuals in my life, including Shri Awadhesh Kumar Shukla (Guru Ji) and Prof. Dr. Renu Kumari (Mata Ji), Prof. Dr. Sanjay Kumar (BRABU), Prof. Dr. Sangeeta Sinha (BRABU), Prof. Dr. Lalan Kumar Jha (BRABU), Late Prof. Dayashankar Mishra (PUP College), Dr. Bishwajeet Kumar Pandey, Nikhil, Dhiraj, Sangeet Chaurasia, Janaki Ji, Ram Pratap, Arun Gope, Shri Chandra Shekhar Singh, Shatabdi, and the entire family.

Thank you to everyone who has been part of this journey. Your support has been invaluable, and I am deeply appreciative of your encouragement throughout this effort. Finally, I express my sincere gratitude to the Almighty for granting me the patience and perseverance to make this endeavor a success.

**With heartfelt gratitude,
Kuldeep Kumar Shrivastava**

List of figures

1.1	Cartoons showing physical realizations of the direct-coupled and side-coupled qubit systems.	4
1.2	Transmission profile, real and imaginary part of eigenvalues for coherent and dissipative coupling of two coupled modes.	7
1.3	Schematic diagrams showing the arrangements of the direct and side-coupled qubits mediums through which the photons are incoming and getting reflected on the left and being transmitted to the right.	10
2.1	Single and two direct-coupled qubits steady-state transmission results	24
2.2	Longer direct-coupled system steady-state transmission.	26
3.1	Single qubit side-coupled to a single resonator transmission results.	36
3.2	Two side-coupled qubits transmission results showing the effects of inter-resonator coupling.	38
3.3	Longer side-coupled system steady-state transmission.	40
3.4	Inhomogeneous side-coupled systems THLE transmission profile for system sizes $N = 3, 4$	42
3.5	Transmission profiles comparing the mod-square of transmission amplitude ($ t_2(\omega_p) ^2$) with transmission probabilities ($\mathcal{T}_{\text{THLE}}^\infty$) for two ($N = 2$) direct-coupled qubits and two side-coupled qubits.	44
3.6	The incoherent component of power spectrum showing inelastic scattering of photons (the two side peaks at higher intensity) for two direct-coupled qubits at resonant input frequency.	45
3.7	The transmission and reflection probabilities along with their sum with increasing ω_p for a system of two direct-coupled qubits and two side-coupled qubits.	47
4.1	Schematic diagram showing two modes A and B with a common signal line and different attributes of the system.	52

4.2	Theoretical calculations of dispersion spectra.	56
4.3	Schematic diagram of planar resonators loaded microstripline for numerical simulation of split ring resonator (SRR) and electric inductive-capacitive resonator (ELC).	58
4.4	Schematic drawing of planar hybrid system comprising of SRR and ELC and $ S_{21} $ spectra of SRR-ELC hybrid sample.	61
4.5	Phase diagrams of CIT and CIA for total dissipation for both the modes and J while keeping $\Gamma = 0$	63
5.1	Cartoon showing an example of the hybrid system having three modes . . .	70
5.2	Two individual level attractions (LA) are tuned to 1 LA + 1 level repulsion (LR)	73
5.3	Cartoon showing an example of the hybrid system having four modes . . .	78
5.4	Three individual level attractions and transition from LA to LR by going through Level-absorption.	80