REVIEW
of the PhD thesis
for obtaining the educational and scientific degree "Doctor" in Physical sciences,
at the Faculty of Physics of Sofia University St. Kliment Ohridski

The review is prepared by: Prof. Stéphane Guérin, University Bourgogne Europe, Dijon, France

Topic of the dissertation: "***Pulse Shape Effects in Qubit Dynamics and Beyond: A Study in Quantum Control on IBM Quantum Processors***"

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General characteristics of the candidate's scientific achievements

The present thesis is about quantum control and more specifically pulse shape effects on qubit dynamics with major applications in quantum technologies and underlying spectroscopy, concretely power superbroadening, power narrowing, and qubit calibration. The pulse shape effects have been moderately studied in the literature while they have a growing importance due to their numerous potential applications in the field of quantum technologies. This study is thus timely. The effects shown theoretically and numerically are demonstrated experimentally on the IBM quantum computer in a very convincing manner.
The detailed original contributions are more specifically: the quantitative benchmark of five commonly used pulse shapes that improve the experimental resonance calibration accuracy, the first experimental observation of power narrowing, the theoretical proposal and experimental demonstration of a new superbroadening effect, and the identification and experimental verification of the concept of isoprobability.
The result about power narrowing have been recently published in a high-level journal, Physical Review Letters. Two other works have been published in Physical Review A, a high-reputation journal and two others are in phase of submission (and can be already found on the ArXiv platform).
The results have been presented in numerous international conferences, schools and workshops (posters and talks).

The manuscript is organized as follows:

Chapter 2 presents a state-of-the-art review of solvable (exactly or approximately) driven two-state models with their realization on IBM quantum computer.

Chapter 3 provides some techniques to solve the time dependent Schrödinger equation (exact, adiabatic and superadiabatic) and the theory of superconducting qubits. These two Chapters prepare the subsequent chapters which contain the original results of the thesis.
The (short) chapter 4 describes the pulse shapes and the hardware parameters of the IBM quantum processors that are used in the subsequent chapters. The main argument is introduced: while at resonance the transition probability is not affected by the pulse shape, it effects become crucial when the deviations from resonance are considered.
In Chapter 5, the dynamics driven by various pulses are studied theoretically via exact results from the literature and approximations. The solution is derived when the pulses have initial and final (finite) asymptotic branches that are linear in time. However, parts of such studies exist in literature [Phys. Rev. A 70, 043402 (2004)] and the novelty of the findings has not been explained. The implementation of these pulses on the IBM quantum computer is next presented in detail. The study is separated into the analysis of two types of pulses: (i) the "common" ones, typically pulses with an infinite support which can be treated by the DDP approach and for which the famous Rosen-Zener conjecture can be tested and (ii) finite pulse shape with a linear slope. Slight deviations between experimental implementations and the theoretical/numerical results. They have been attributed to the non-linearity of the Qiskit amplitude parameter with respect to the Rabi frequency and the possible leakage to higher levels.
Chapter 6 addresses the power narrowing and superbroadening effects. Power narrowing appears when a Lorentzian shape is truncated at large times. The scaling factor of such narrowing is given. Power superbroadening is analyzed with the use of quadratic and even exponent pulse shapes, referred to as face-changing pulse shapes.
Chapter 7 addresses the question of isoprobability models with time-dependent phases (while the preceding chapter makes use of constant detuning) by the Delos-Thorson approach. More specifically, the phase of the Rabi frequency is used to generate an effective time-dependent detuning since the latter is not directly accessible on the IBM quantum computer.
Chapter 8 concludes the work with a summary of the key findings and the limitations (higher-dimensional systems (two-qubit systems), systems with specific experimental constrains, presence of noise and decoherence).

Critical remarks, questions and recommendations

The PhD thesis is written in a very good English; it is relatively well organized and presented. I can just notice that the very short Chapter 4 could certainly be merged with another one.
The state-of-the-art about driven quantum two-state systems shows the solid knowledge of the candidate about them. There are, however, some shortcuts in the presentation with missing references, most notably concerning the growing field of optimal control (see below). My opinion is that this study with many analytic results (demonstrated on the IBM quantum computer) complements very well the optimal control techniques which often (but not always) leads to purely numerical pulse shaping.
The thesis has resulted in three published peer-reviewed articles of very high quality (Physical Review Letters and Physical Review A), and two others are available on the ArXiv platform. Ivo S. Mihov is the first author of all these papers, which expresses the recognition of his significant contribution. These publications demonstrate the high quality of the thesis. In addition, the candidate has presented a large number of communications (oral presentations and posters) in international conferences related to his PhD thesis.

I have the following questions to be addressed during the defense:

- The shift introduced in the bottom of p.3 is referred to a phase noise while it appears as a noise on the Rabi frequency. This should be commented.

- The method proposed in Section 5.2 looks similar to the one developed in the paper Phys. Rev. A 70, 043402 (2004). This reference should be cited, and the differences with this work should be highlighted.

- Concerning the finite pulse shape with linear asymptotes, why only linear slope is considered? What do we expect for polynomial or exponential asymptotes?

- Leakage to higher levels (than the two qubit states) is mentioned (p.70-71) and possibly identified by an asymmetry of the excitation landscape. We know that such leakage is inevitable in the superconducting systems and should appear for strong driving with fast switching. Has this leakage been more clearly characterized on the IBM computer? Would it be a way to clearly identify it with Qiskit tools?

- In conclusion of Chapter 6, an application of power superbroadening is mentioned as a way to excite off-resonant transition. This appears similar to techniques that allow to improve the robustness with respect to detuning by broadband pulses (in the context of power broadening). Such techniques include the use of composite pulses. Here the advantage would be in the pulse shaping instead of a composite pulse sequence. Note also that this has been also addressed by optimal control [see e.g. Phys. Rev. A 109, 062613 (2024), Section 7], where an optimal pulse shaping features a broadband excitation profile. This should be commented.

- How does the Delos-Thorson approach generalize to higher-dimensional systems (N-level systems)?

I have the following additional comments:

- In p. 19, it is mentioned: "it seems that phase modulation not only provides an alternative to time-dependent detuning but also improves the robustness and fidelity of the control."
  However, such improvement of robustness by a time-dependent detuning or equivalently a phase modulation has been precisely shown in Phys. Rev. Lett. 125, 250403 (2020), where a specific oscillating detuning with a constant Rabi frequency amplitude induces an optimal robustness, determined by optimal control. This should be included and commented.
  More generally the growing techniques of optimal control for quantum control are not mentioned and cited in the manuscript, while these techniques often result in pulse shaping [see e.g. Quentin Ansel, Etienne Dionis, Floriane Arrouas, Bruno Peaudecerf, Stéphane Guérin, David Guéry-Odelin and Dominique Sugny, Introduction to Theoretical and Experimental aspects of Quantum Optimal Control, J. Phys. B 57, 133001 (2024)]. They appear thus strongly related to the present study.

- In p.24, section 3.3: the superadiabatic bases has a long history not limited to Ref. [176], for instance: M. V. Berry, Proc. R. Soc. London A 429, 61 (1990); A. Joye and C.-E. Pfister, J. Math. Phys. 34, 454 (1993); K. Drese and M. Holthaus, Eur. Phys. J. D 3, 73 (1998). This should be added.

- In p.39, the references given concerning the DDP formula are incomplete. The generalized DDP formula has been first shown in A. Joye, H. Kuntz, and Ch-Ed. Pfister, Ann. Phys. 208, 299 (1991) and A. Joye, G. Mileti, and Ch-Ed. Pfister, Phys. Rev. A 44, 4280 (1991). This should be mentioned.

- In p.41, Ref. [26] appears incomplete.

Conclusions

I am convinced that the theoretical results and demonstrations on the IBM quantum computer presented in the thesis will have a strong impact in the field of quantum information as pulse shaping effects will have an impact for a large variety of systems (qudit, platforms, control, …).
The dissertation, abstract, and the quality of the scientific publications submitted by Mr. Ivo Mihov meet the requirements of the Faculty of Physics at Sofia University “St. Kliment Ohridski.” Therefore, I support the awarding of the educational and scientific degree of "Doctor."

Prof. Stéphane Guérin