Quantum Batteries: Technology and Advancements

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Abstract – In the quickly advancing field of quantum technology, it is of great importance to assess the current state of knowledge regarding this field. Moreover, considering the application of quantum technology to battery management systems, the opportunities, issues, and challenges associated with quantum batteries need to be studied. This paper provides a review of quantum technology and describes the current developments related to quantum batteries.

Keywords—Spinning,Coherence,Entanglement, Superposition, Quantum Batteries

I. Introduction

In this paper we will discuss the technology of quantum batteries, their existence, practicality, current advancements, future focus, and potential benefits. It should be noted that quantum technology is on the brink of discovery, and this paper should be read as a review of the current theories, methods and plans held by researchers and scientists at the forefront of this ever-expanding field. Since a practical fully functioning quantum battery is yet to be produced, this paper will focus on the background understanding of how the currently proposed models' function, its planned impact, and recent breakthroughs in the many inherent problems. The overall aim of this paper is to inform the reader of current advancements and fill gaps of knowledge regarding the theory of quantum energy storage.

The first section in this paper will cover the current outlook of the field of quantum batteries. We will discuss the theory of the current working model. This will include how the charging, containing, and dissipating of energy works in a quantum system, how miscellaneous factors, such as the environment, affect the system, and how quantum batteries are the solution to other problems in quantum mechanics. Secondly, we will cover current progress. In this section we will explore the current research that is being done and its implications. This section is particularly exciting as it will highlight very recent research and results that are extremely important to quantum systems.

In the third section we will cover the future advancements that are being pursued currently. Many of these advancements are widely centered around the common goal of being able to functionally produce these batteries as practical models able to be utilized by the common consumers in products such as electric vehicles, phones, and everything in between. Overarchingly, we will focus on the goals in the field and the experts' outlook for potential progress and advancements. This will bring us to a great conclusion, hopefully providing a clear view into the future of quantum systems. Lastly, we will conclude our paper with a succinct assessment of the field of quantum batteries and its potential ability to positively impact our lives in the future.

II. Current Technology

Within the last five years many breakthroughs have been made in the field of quantum energy storage, but to understand this progress we must first cover the theory that makes quantum batteries work. We want to start by looking at the model of an atom as discussed by Ziroth [1]. Although there are several ways to model an atom, we will focus on the electron cloud model (Figure 1), as it is the most advantageous for our understanding. In the cloud model we see the electrons swarming around the nucleus. If we take a single layer slice out of that cloud, we will have something that looks like our second model as shown in figure two. In this view we can get an idea of what is happening during quantum charging, however we will zoom in further, so that we view the rings of the atom as rungs on a ladder (Figure 3).

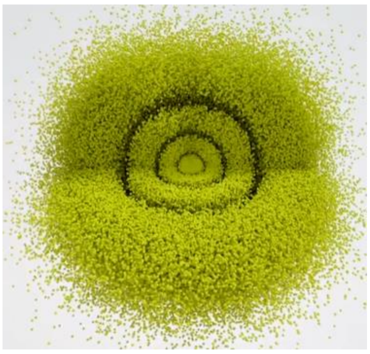

Figure 1: Cloud Model of an Atom [1]

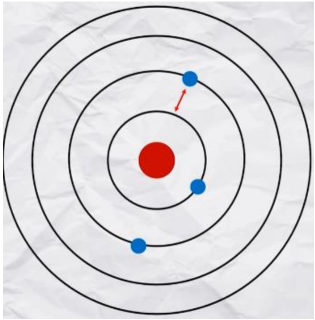

Figure 2: Section View of an Atom [1]

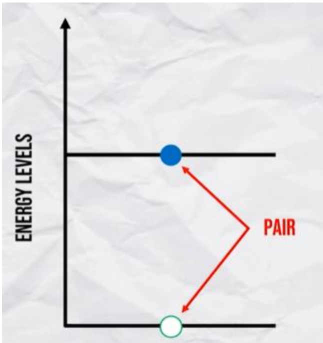

Figure 3: Ladder View of an Atom Diagram [1]

Figure three lends us the ability to understand the core principle of quantum energy storage. As the atom is charged the electron moves further from the nucleus, and stores more potential energy [1]. Once the electron has traveled to its outmost position it will store its maximum energy. Once released the electron will naturally travel back to its original position dissipating the stored potential energy. By doing this process to several electrons in many atoms we can achieve what is proposed to be a functional quantum battery. Unfortunately, there are some challenges to achieve this. One of the primary issues is the matter of holding the electron in its “charged position” [1]. Ziroth refers to this process as putting the electron in to a “dark state”. This proposed dark state would allow the electron to hold the charge given to them for as long as desired, and upon removing the dark state, the electron would naturally move to its original position discharging off its extra energy [1].

An additional issue is that of properly extracting the dissipated energy as the electron moves back. As Ziroth and Campaioli et al. both describe it, this may be possible via the same technology that is used to capture energy from solar power systems [2]. Campaioli et al. additionally dives deeper into the charging, storage, and extraction practicalities within quantum batteries. In a phenomenal plot, Campaioli et al. shows the function of a quantum batteries ability to be cycled through the typical use case (Figure 4). This graph shows the amount of energy loss over time in storage as it relates to the entire process.[2] As done in his paper and shown on the graph, the “relaxation rate” $-T_r^{-1}$ of this which is found to be equal to $\dot{E}$ divided by E.[2] This information is critical knowledge as we continue to try to explore the possibilities of quantum batteries and what they may be able to do in the future.

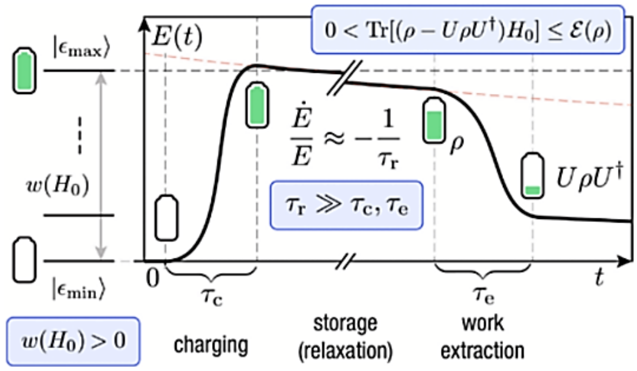

Figure 4: Plot of the life cycle of a quantum battery, including inequalities expressing the function of each section. [2]

In a continuation to fully understand the storage life of energy in these batteries, Santos et al. covers an additional concern and factor that may lead us to more progress [3]. In his paper Santos et al. discusses how in the current model we don’t have a perfect way to put these charged electrons into a “dark state”. As soon as the battery reaches its maximum, it begins to discharge. Using methods like spinning, entanglement, superposition, or coherence, Santos et al. looks at the potential for using a three-tiered battery system, in hopes to be more substantial in its environment [3]. These studies bring us up to date with the background knowledge needed to understand the new progress currently being made, which we will discuss in the next section.

III. Current Progress

Many researchers currently have ongoing research on quantum batteries that address all the problems we previously discussed, and many other smaller challenges that plague quantum battery technology. As covered in the research by Santos et al., the storage of such energy within the system can be a challenge, however they additionally propose in their paper that by using Stimulated Raman Adiabatic Passage (STIRAP) in a three-tier system, they could stabilize the battery in its environment, potentially leading to a fully usable system [3]. In the paper, this new approach works mathematically and will hopefully lead to a functional method utilized in a one-day real life prototype.

In another paper Rodriguez et al. tries to tackle the challenges of charging such battery systems most efficiently, and in a hope to discover whether this technology will truthfully carry as much impact as is hoped for. Through his research it was found that charging the battery with a laser is by far the best option for charging [4], as simplistically demonstrated in the graphic (Figure 5). Moreover, it is found that by using a Gradient Ascent Pulse Engineering algorithm (GRAPE), it is possible to achieve the most efficient and effective method for charging a quantum battery [4]. It should also be noted that this system would be able to be scaled and additionally increase its efficiency

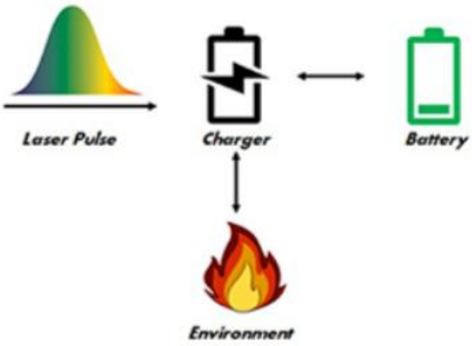

Figure 5: Diagram of the sequence a quantum battery charger undergoes [4]

In the same research direction, Siddique et al. also conducted research pertaining to the charging of quantum batteries [5]. Siddique et al. found that the strength and frequency of the laser used to charge the battery made drastic impacts on the response and performance of the battery [5]. As shown in Figure 6 and Figure 7 below, the tuning of the frequency can drastically change the response of the battery, as well as choosing the ideal driving method.

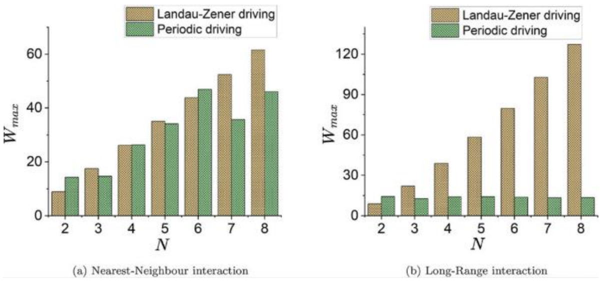

Figure 6: Graphs of Max Work Vs Number of Spins for both common interaction types, parameter: $g = 10B$, $\omega = 4B$, $\gamma = 1.0$, and $v = 10B$. [5]

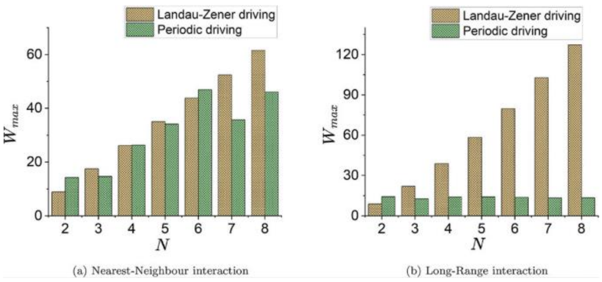

Figure 7: Graphs of Max Work Vs Number of Spins for both common interaction types, parameter: $g = 10B$, $\omega = 4B$, $\gamma = 1.0$, and $v = 10B$. [5]

Both Rodriguez et al. and Siddique et al. present good progress in charging technology for quantum energy storage systems.

IV. FUTURE ADVANCMENTS

When it comes to future advancements for quantum batteries, much more research is needed. To continue our discussion of the challenge of charging a quantum battery however, Wang et al. [6] made some interesting findings in their research and left the door open for more research to be continued in this area. Wang et al. focused heavily on making the charging system for quantum batteries as efficient as possible. Like Rodriguez et al. and Siddique et al., they found the strength and frequency of the laser used in the charging process providing a significant advantage to the system's efficiency [6]. Specifically, they found that if the external driver has non-resonance, it is much more efficient (Using the set up as shown in Figure 8), which is very similar to the findings of Siddique et al. However, it was found that entanglement between the charger and the battery had no improvement in efficiency. Additionally, it should be noted that Wang et al. utilized a two-tier system, as opposed to the three-tier system and it was found to be better according to the research done by Santos et al.

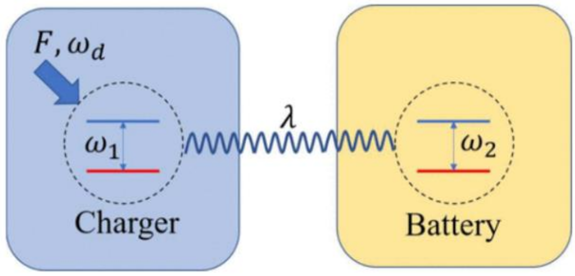

Figure 8: Diagram showing the general format for testing the efficiency of external non-resonance drivers in charging quantum batteries. [6]

In addition to the research work done by Wang et al., other research was conducted focusing on the true advantage of quantum batteries, focusing on their charging ability, and dissipative capabilities. The research conducted by Andolina et al. concluded that the current state of quantum energy storage systems is mathematically capable of functioning at the quantum speed limit [7]. This means that the process of charging and discharging can be completed far faster than any current comparable system we have. An article by Tuhin describes the importance of this breakthrough and the many others like it, this "could redefine what's possible in science, medicine, and industry" [8].

V. CONCLUSIONS

In conclusion, it is clear that the field of quantum systems, and particularly quantum batteries, is rapidly advancing and will hopefully continue to reach breakthroughs for many years to come. At the current pace of advancement paired with the high amount of interest by researchers, the outlook is great for the future of the field. The mass production and widespread usage of this technology is still expected to be a long way off. Experts hope that within the next few years a practical model will be produced that could be refined from there. Overarchingly the current state of quantum batteries is ever changing and exciting. Questions, and challenges about charging, storage, and discharge are still plentiful, and experts still contest about the true model and understanding of how the quantum system specifically works. Yet, the potential for rapid charging batteries that lose minimal energy, and deliver instant charge, is too promising to not pursue. The economic and environmental impacts from such technology would drastically change the landscape of how we live, and so it is therefore paramount that we continue to research, and study the possibilities and advantages of quantum technology, specifically quantum batteries.

Conflict of Interest

The authors declare that they do not have any conflict of interest.

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