Supercharged!: Advances in Superabsorbance for the Development of Quantum Batteries

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As the world shifts away from fossil fuels and towards renewable energy sources, it is becoming increasingly important to develop systems which can store electricity and release it when necessary. Classical batteries are excellent at these tasks, but the rates at which they charge have acted to prevent the widespread adoption of many green technologies including electric vehicles.[1] While significant research efforts have been put into developing rapidly charging batteries, all the material focused research is based on electrochemical principles dating back over two centuries. These efforts have provided many advances in battery technology, but they ignore the progress made in other areas of chemistry. To take advantage of these advances, a new class of batteries has been proposed: the quantum battery (QB).[2]

There has been extensive theoretical research into QBs and while many models have been proposed that would take advantage of quantum mechanical properties to realize a rapidly charging QB, only a few exhibit charging rates faster than a classical battery. To compare the quantum and classical batteries, the rate that the charging power scales with the number of cells in the battery is typically calculated. Charging power is defined as the ratio of the amount of energy stored to the amount of time required to store that energy.[2] To generalize this comparison between different models, this is then compared against the number of cells in the battery, to determine how it scales. For classical batteries each cell is isolated and charged in parallel, so the charging power scales linearly with the number of cells.[1] That is if a battery with n cells is to be charged classically, it would have a maximum charging power per cell equivalent to $\alpha n^{\beta-1}$ where $\alpha=\beta=1$. However, for QBs the cells need not be isolated as they can interact via quantum mechanical interactions. This can give rise to a so-called quantum advantage, where α or β are greater than unity.

One of the most widespread models in chemistry is the two-level system (TLS) and rather unsurprisingly, it has been adapted to model a QB. In a QB composed of TLSs, each system has been embedded in and coupled to a cavity. Analytical research shows this gives rise to a quantum advantage. When analytically determining the maximum charging power it has been found to scale as the number of cells raised to the 3/2 power, or mathematically as αn^{β} where $\alpha=1$ and $\beta=3/2$.[3] To evaluate the quantum origins of this advantage, the system was compared to its classical analog. Without allowing the interactions
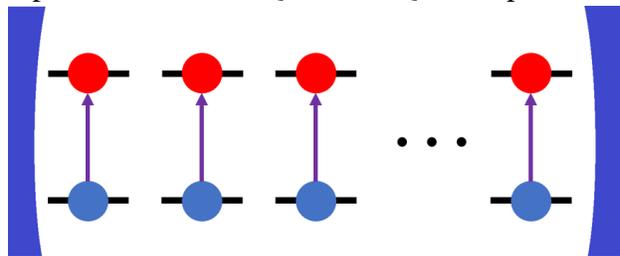

Figure 1 A typical Dicke QB, many TLSs are embedded in a single cavity allowing all to be entangled with a single photonic mode. When the battery is completely discharged each TLS is in the ground state and when charged, each is in its excited state. Adapted from reference 2.

between TLSs, the classical model shows no advantage in charging power, as such a series of TLSs coupled to a cavity has shown the potential to make a QB.[3] Further theory research has shown this advantage is independent of the coupling strength of the TLSs to the cavity.[2] This battery has been deemed the Dicke QB and being one of the simplest models, a prototype has recently been developed.

      One of the properties preventing the experimental realization of a Dicke QB is the inability to create a system that can be entangled by the absorption of energy from a quantized electromagnetic source. In 1954, physicist Robert Dicke, for whom the Dicke QB is named, developed a model to describe radiation with strongly interacting molecules; he called this process superradiance.[4] In this model, N dipoles interact coherently then, if one dipole beings to radiate, other molecules also begin to radiate. This causes the rate of radiation to be proportional to N^2 as opposed to the N for standard emission processes. After nearly two decades, superradiance was supported by experimental evidence in HF gas and since the initial study, superradiance has been seen in a variety of systems from molecular aggregates to nitrogen-vacancy centers.[5][6][7]

      However, QBs rely not on superradiance, but instead on the much more elusive superabsorbance. Superabsorbance is the reverse of superradiance such that a set of N interacting dipoles absorb not a rate proportional to the number of dipoles, but instead as the square of the number of dipoles.[8] This process is much less intuitive than superradiance, and on the surface, it may seem as if it should not be real. But, absorption and emission processes are time symmetric, meaning that if superradiance exists, then its reverse process of superabsorption must also exist.[8] Despite knowing this process exists, it took nearly half a century since the first experimental evidence of superradiance was seen, for superabsorbance to be realized.

      Yang et al. were the first to demonstrate experimental evidence of superabsorbance by exploiting time-reversal symmetry.[9] They used a series of two-level ^{138}Ba atoms transitioning from the $^1S_0$ to the $^3P_1$ state. These atoms placed on a grid and are then excited by a pump laser. The placement of the atoms on the grid gives rise to a superradiant state. Hoping to reverse the superradiance, Yang et al. then prepared the same system in an orthogonal state. In this state, they were able to observe the atoms absorbing photons instead of emitting them. Comparing the rate of absorbance in this system to the absorbance of a normal, nonsuperradiant system showed the rate was higher in the state orthogonal to the superradiant state.[9] This indicates the first experimental evidence of superabsorption.
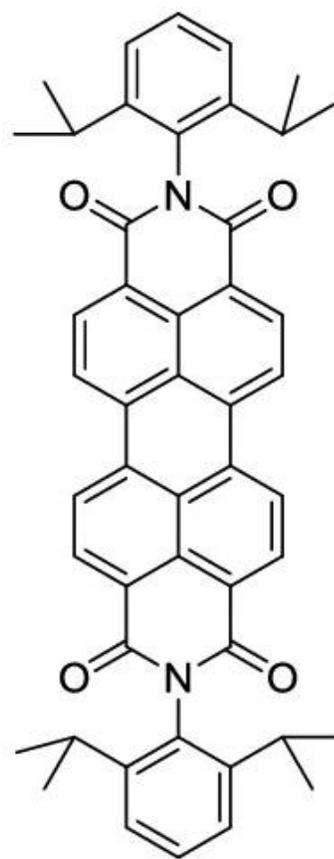

Figure 2 Lumogen-F orange, the organic semiconductor used in the first realization of a QB. When exciting the 0-0 transition, this molecule is effectively a TLS.

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Building on this work, a prototype of the Dicke QB was first realized in 2022.[10] This battery utilized a common organic semiconductor, Lumogen-F orange, as the two-level system. Using ultrafast optical transient absorption to measure the charging and energy storage properties of this system, shows experimental QBs can realize the theoretically predicted advantages. Quatch et al. showed that this system can utilize the superabsorptive properties of its component molecules to offer advantages that scale with size.[10] For example, in these QBs more rapid charging is achieved by having a system composed of more molecules because each molecule absorbs more energy than it needs to enter its exited state and this extra energy is used to excite other molecules.

But, despite realizing the very first QB, significant advances still need to be made before this is a practical device. The battery that Quatch et al. developed shows superabsoprtion and rapid charging, however it also shows rapid discharging such that this device could never be used to make a practical device.[10] To stabilize the energy and prevent rapid discharging more work needs to be done. Additionally, theoretical research has shown that the Dicke battery is not the most efficient QB as the maximal increase in charging power is quadratic with the number of cells while the Dicke battery is proportional to the number of cells raised to the 3/2 power.[1][3] So, while the realization of superabsorption by the exploitation of time-reversal symmetry has allowed the first QB to be developed, significant advances need to be made to develop usable devices.

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