Beyond discrete time crystal signatures: hidden coherence, causes of decay, and the first 'discrete time crystal echo'

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The phase structure of driven quantum systems can include exotic phenomena, including the recently-described discrete time crystal (DTC), which is a robust phase that breaks the discrete time translation symmetry of its driving Hamiltonian. If the driving Hamiltonian has period T, the key signature of a DTC is a response which instead has period nT (with n=2,3,4,…), even when the drive is imperfect. Two experiments recently demonstrated this signature, one in trapped ions [1], and the other in diamond NV centers [2]. We have shown this signature in an NMR system of 31P spins on a crystal lattice, where we use cross-polarization between 31P and 1H to rapidly repeat our experiments. We "drive" the system with repeated pulses of angle theta, with delays of time tau between the pulses (the "DTC sequence"). For long-enough delays tau between pulses, we have observed strictly "up-down" oscillations of the magnetization (so-called "DTC oscillations"), even when theta is adjusted slightly away from pi [3,4].

As in prior experiments, we observe DTC oscillations that eventually decay. An open question has been the cause for this decay of the response. Here, we study these phenomena in more detail, with two main results. First, we devise a novel "DTC echo" sequence to probe the coherence in the system. We observe clear echoes, demonstrating that the original pulse sequence is driving coherence to unobservable parts of the density matrix. This indicates that the decay of the original signal is caused in part by coherent evolution.

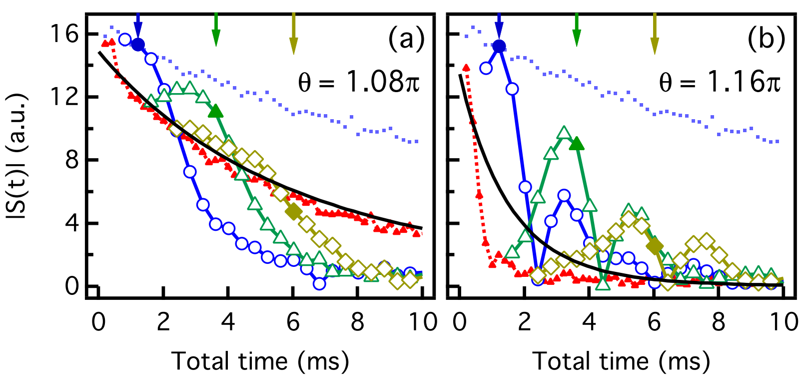

Figure 1: Echoes rising above the original "DTC sequence" signal, for two different rotation angles, (a) theta = 1.08pi and (b) theta = 1.16pi. We treat the original "forward" evolution like the part of a Hahn echo sequence before the pi pulse (the full forward evolution is shown in red). After N "forward" cycles, we switch to the echo part of the pulse sequence, which is like the part "after the pi pulse" in a Hahn echo sequence. For N=2,6,10 (blue, green, yellow), we see clear echoes rising above the original decay, which are expected to peak at N', indicated by the arrows and filled markers.

Second, we study the observed decay for epsilon = 0. After exhaustively ruling out experimental sources for this decay, we show that the action of the internal Hamiltonian during the pulses can produce this decay. We demonstrate the importance of the pulse duration by altering the original "DTC sequence," using pi pulses of difference phases. Since the pulse phase should not matter for perfect pi pulses in the delta-function pulse approximation, this allows us to isolate the effect of the internal Hamiltonian during the pulses – in Figure 2, we see that this effect is significant. This will be an important limitation for any experiment which strives to determine an 'intrinsic' lifetime for DTC order.

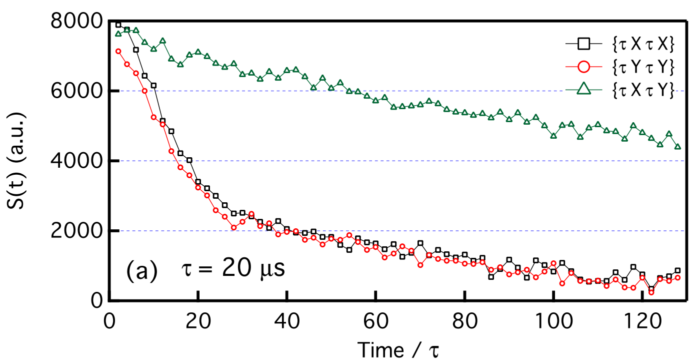

Figure 2: For theta=pi, the original "DTC pulse sequence" should be independent of the phase of the pi pulse, in the delta-function pulse approximation. However, we see a dramatic difference in lifetime between using either two X-phase pulses (fast-decay, black) or two Y-phase pulses (fast-decay, red), versus using alternating X-phase and Y-phase pulses (slow decay, green).

[1] J. Zhang et al., Nature 543, 217 (2017).
[2] S. Choi et al., Nature 543, 221 (2017).
[3] J. Rovny, R.L. Blum, S.E. Barrett, arXiv:1802.00126 (2018).
[4] J. Rovny, R.L. Blum, S.E. Barrett, arXiv:1802.00457 (2018).