CPMG with Time-Dependent Fields: Observation of Adiabatic and Non-Adiabatic Behavior

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We present experimental results and a new theoretical framework to analyze the effects of time dependent magnetic and RF fields on the spin dynamics of the Carr-Purcell-Meiboom-Gill (CPMG) sequence. The theoretical analysis is based on the decomposition of the magnetization into the eigenmodes of the propagator of a single refocusing cycle. For sufficiently slow changes in the external fields, the magnetization follows the changing eigenmodes adiabatically. This results in echo amplitudes that show regular modulations with time. Faster field changes can induce transitions between the eigenmodes. Such non-adiabatic behavior occurs preferentially at particular offsets of the Larmor frequency from the RF frequency where the eigenmodes become nearly degenerate. We introduce the instantaneous adiabaticity parameter $\mathcal{A}(t)$ that accurately predicts the crossover from the adiabatic to the non-adiabatic regime and allows the classification of field fluctuations. $\mathcal{A}(t)$ is determined solely by the properties of a single refocusing cycle under static conditions and the instantaneous value of the field offset and its temporal derivative.

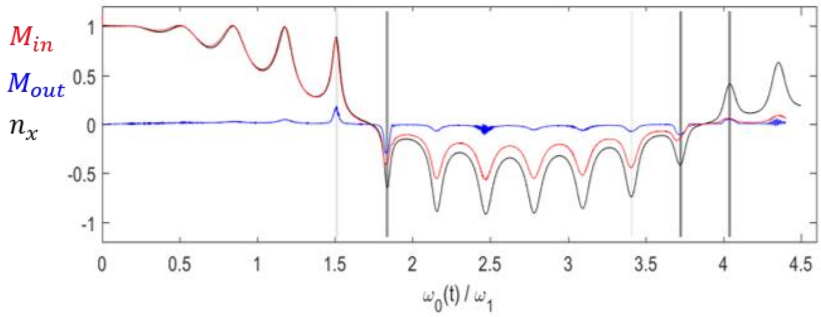

Fig. 1: Experimental CPMG results for in- and out-of-phase echo amplitudes in an increasing magnetic field versus normalized offset of the Larmor frequency. Theory for adiabatic limit is shown in black. Non-adiabatic events occur when the adiabatic condition $\mathcal{A}(t) \gg 1$ is not fulfilled (gray shading).

In the adiabatic regime when $\mathcal{A} \gg 1$, the impact of field variations is fully reversible. This is demonstrated experimentally in Fig. 2 for the case when the field is ramped up and down. When the conditions for the field sweep is entirely in the adiabatic regime, the final magnetization fully recovers the value that is observed in a stationary field. When the ramp includes non-adiabatic regions (shown as black bands), the magnetization at the end of the ramp is reduced. The locations of the non-adiabatic regions occur precisely at the anticipated offset fields when the eigenmodes become nearly degenerate.

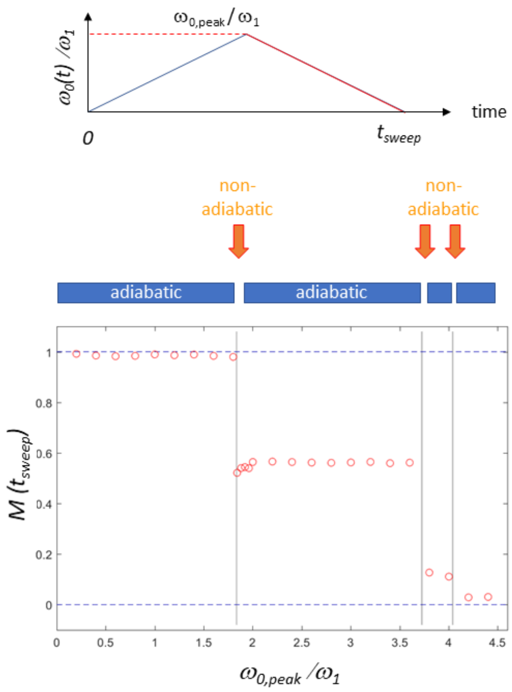

Fig. 2: Experimental CPMG results of the magnetization at the end of the sweep, t_{sweep}, versus the amplitude of the field sweep. The location of the non-adiabatic regions are clearly evident and coincide with the theoretically prediced locations, shown as gray shading, where the eigenmodes become nearly degenerate.