Low-Frequency Modulation of the Longitudinal Field: Modified Rabi Envelopes

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The sensitivity of Rabi oscillations to low-frequency modulation (5-100 kHz) of the static longitudinal magnetic field B_0 is studied [1]. Three regimes are considered: strong modulation (compared to the driving field strength B_1, ~1-10 G), fast modulation (compared to the non-modulated Rabi frequency Ω_R), and weak/resonant modulation. The experiments are straightforward to achieve in the laboratory, but can be mapped to more unconventional NMR conditions where B_1 strength is much greater than B_0. The theoretical predictions were tested with a two-coil probe using protons in water doped with copper sulfate in a 88.8 MHz field, where Rabi oscillations could be observed over many periods. We present experimental results that agree with the predictions quantitatively.

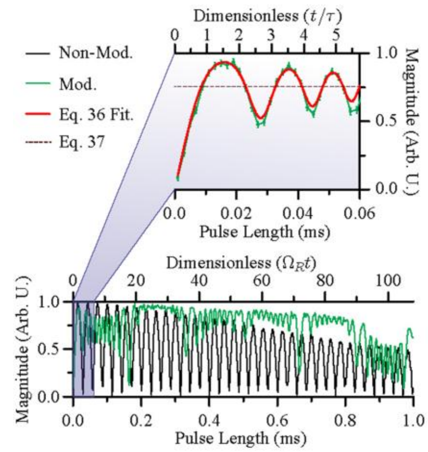

Figure 1. The effect of strong-slow modulation on Rabi oscillations is shown. This regime can be mapped to a strongly-driven, non-modulated system

The mapping of a weakly driven two-level system with modulation onto a strongly driven system without modulation suggests that different regimes of spin dynamics, previously known for a strongly driven system (i.e. multiphoton resonances [2-4]), can be realized under easily accessible conditions with proper choice of modulation frequency and amplitude. Strong-slow modulation is seen in Figure 1, where seemingly complicated data is well understood using analytical calculations (which are heavily dependent on the initial spin-state beginning on periodic intervals that are determined by modulation frequency). In the extreme limit of this regime, the longitudinal field is essentially swept into and out of resonance, but the analytical derivation remains valid for achievable experimental conditions. In particular, we find the early-time data shown in the top part of Figure 1 is completely predicted analytically.

Fast-strong modulation emulates the regime of a driving frequency ω much larger than the resonant frequency γB_0 and B_1 strength much greater than B_0. Similar to experimental results in atomic physics, an effectively shorter magnetic moment is created (from averaging due to the fast modulating field) that causes a slowing of the Rabi frequency. Additional corrections are required when using a strong modulation strength, and are also seen experimentally.

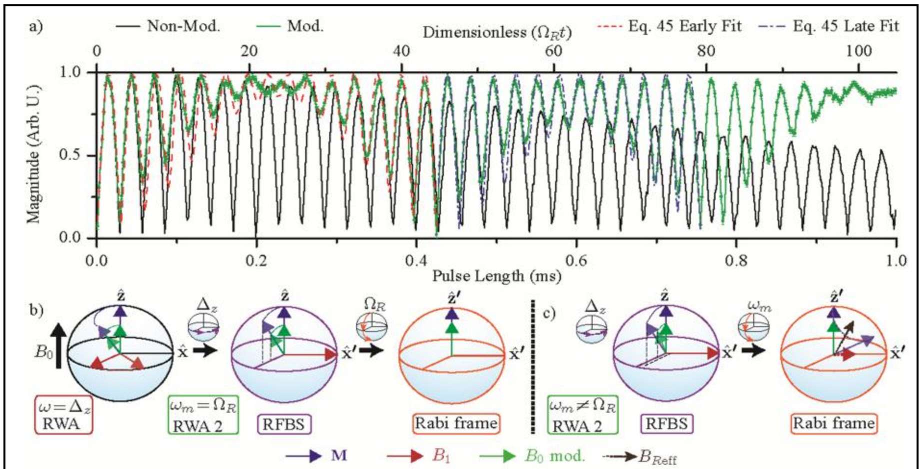

Figure 2. a) Shown are the results of a weak/resonant modulation and its effect on the Rabi envelope. b) This regime lends itself to a convenient doubly rotating-frame Bloch sphere (RFBS) picture, the Rabi frame.

Weak/resonant modulation gives rise to an envelope of the Rabi oscillations. The shape of this envelope is highly sensitive to the detuning of ω and strength of modulation field. Data is shown in Figure 2a, where a departure from the non-modulated Rabi oscillation is seen, with a fits using a function derived from Floquet analysis [5]. The weak modulation strength allows one to make a second rotating-wave approx. (RWA), shown in Figure 2b, to a doubly rotating frame called the Rabi frame.

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