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Noise enhancing coherent oscillations at a Landau-Zener transition

Quantum systems can be in a coherent superposition of two different states. These "Schrödinger cats" are characteristic of the quantum world and cannot exist in classical mechanics. Coherent superpositions are identified by the coherent oscillations of observables. However noise (of a quantum or classical origin) is a huge impediment to observing or using such coherent superpositions. Even a small amount of noise causes the decoherence of quantum superpositions into classical mixtures: the noise makes the quantum system lose this essential quantum property, stopping the cat being in a superposition of "dead" and "alive".

Quantum noise originates from the system's coupling to other quantum degrees of freedom in its environment, while classical noise is due to random fluctuations in classical (macroscopic) fields coupled to the quantum system. Macroscopic systems typically couple strongly to many degrees of freedom, and thus decohere too fast for superpositions to be observable. Even small systems, such as molecular magnets or nanoscale superconducting circuits, decohere sufficiently fast that it is impracticable to use their superpositions for applications such as quantum computing. As a result, there is currently research on superpositions in many different quantum systems, with the objective of understanding the origin of the noise which causes the decoherence in each of them. However, in a recent work we show that under certain conditions the noise can also *enhance* the coherent oscillations that appear when a quantum system is driven through an avoided level crossing.

Such an enhancement can occur because noise does not only cause decoherence, it also *modifies* the system's Hamiltonian. Such a modification was first proposed by Hans Bethe as an explanation of the Lamb shift of energy levels in the hydrogen atom. There the noise source is the vacuum fluctuations of the photon field. This noise certainly has a decoherence effect, however the crucial point was that it modified the Hamiltonian of the atom sufficiently to create a shift of certain energy levels.

In 1932, Landau, Zener, Stueckelberg and Majorana independently addressed the problem of a quantum system being driven through

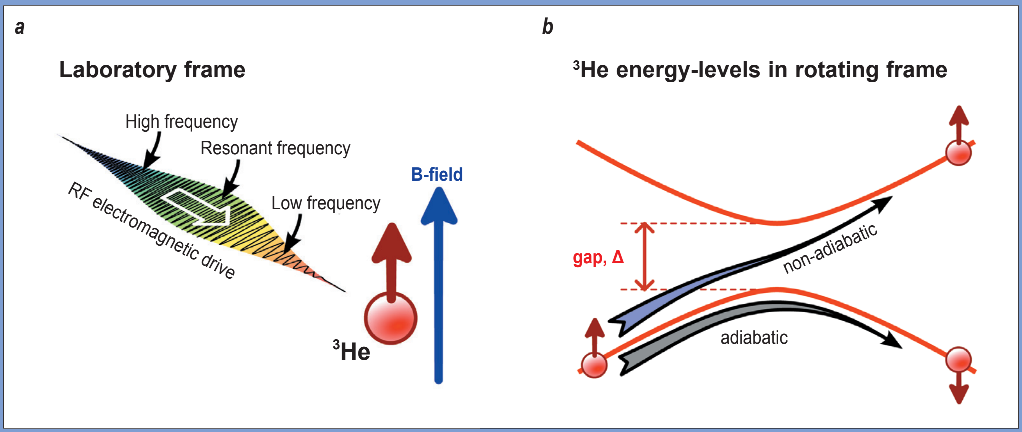

Figure 1: *A ^{3}He atom whose spin is driven by a radio-frequency electromagnetic (EM) field whose frequency changes with time. In the rotating frame this has the effect of sweeping the system through an avoided crossing. For a large gap, the Landau-Zener transition is adiabatic. For smaller gaps, the system passes into a superposition of the two states (ground and excited state). A Lamb-shift of the gap modifies this superposition.*

Quantum systems can be in a superposition of two different states at once. Such superpositions can be detected by looking for coherent oscillations of observables. Usually noise decoheres superpositions and thereby suppresses coherent oscillations. However we showed that noise may enhance the coherent oscillations of a system driven through a Landau-Zener transition, via an effect we call "Lamb-assisted coherent oscillations". We propose verifying this with polarised ^{3}He, before using it as a probe of the sources of quantum noise which affects molecular magnets.

an avoided level-crossing, see **figure 1b**, a problem now known as the Landau-Zener transition. They showed that the transition amplitude from the ground state to the excited state has an exponential dependence on the gap at the avoided crossing, Δ. We therefore argue that this amplitude will be exponentially sensitive to any noise-induced Lamb shift of this gap. The sign of the Lamb shift is a function of the noise-spectrum (noise at higher frequencies than Δ reduces the gap, while noise at lower frequencies enhances it). If the Lamb shift reduces the gap slightly, then the small transition amplitude will be exponentially enhanced, exponentially magnifying the coherent oscillations. We show that this effect, which we call "Lamb-assisted coherent oscillations", often dominates over the decohering effect of the noise.

Highly polarised ^{3}He is an ideal testing ground for our theory. Each ^{3}He atom has a spin-half which can be flipped by electromagnetically driving the system at radio-frequencies. In the rotating frame, the spin-flip can be seen as a Landau-Zener transition. Since all atoms in the gas behave in the same manner, the time-dependence of a ^{3}He atom's spin-state is observed by measuring the magnetisation of the whole gas as a function of time. The intrinsic noise in the system has been made extremely small (decoherence times are relatively long) thanks to recent work within the Nuclear and Particle Physics group at the ILL. However it is very easy to add man-made noise in a controlled manner. In addition to testing our theory (which assumes the noise to be a weak perturbation), a ^{3}He experiment can be used to study the effect of strong noise on Landau-Zener transitions.

These "Lamb-assisted coherent oscillations" could be used as a probe of the source of noise in various quantum systems, since its temperature dependence is a function of the noise-spectrum. One should thus distinguish high-frequency noise (which enhances the coherent oscillations) from white-noise or low-frequency noise (which both suppress the oscillations). For example, this could help resolve the current debate about whether the principle source of decoherence in molecular magnets is a low-frequency bath of nuclear spins, or a high-frequency bath of phonons.

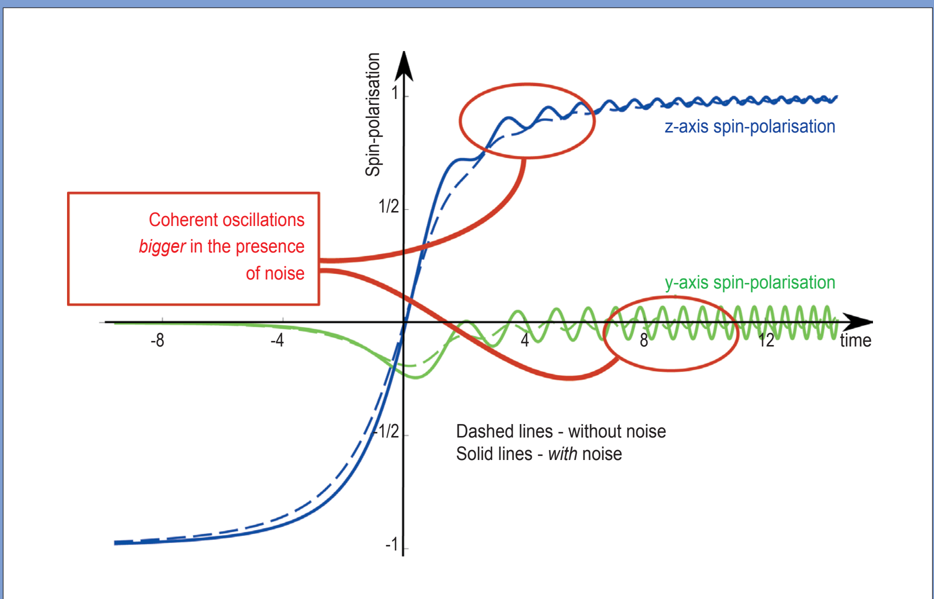

Figure 2:
The spin-polarisation of the ^{3}He atom measured along the y and z axis, as a function of time.
Noise clearly enhances the coherent oscillations.