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A liquid of identical molecules as first-of-its-kind comagnetometer

Researchers from the Helmholtz Institute Mainz built a comagnetometer based on an ensemble of identical molecules.

A magnetometer measures magnetic fields and, perhaps, additional exotic fields. A comagnetometer measures magnetic fields twice. When the two measurements subtracted from each other, researchers search for any residual interaction, which could be a signature of new physics.

Previous liquid-state nuclear spin comagnetometer (Phys. Rev. Lett. 108, 243001, 2012) used ^{1}H in pentane and ^{19}F in perfluorobenzene as the two types of spins interacting with magnetic fields. But even in miscible liquids, temperature gradients caused problems. For example, position-dependent magnetic fields interact differently with ^{1}H and ^{19}F since thermodiffusion generates a concentration gradient of the two types of molecules.

Thus the problem is: you need two magnetic field measurements to look for tiny effects, but when you use two different molecules to interact with the magnetic fields, the molecules tend to end up in different places (at least a little bit).

Solution: use one type of molecule that provides two measurements of magnetic fields.

In a recent article (Phys. Rev. Lett. 121, 023202, 2018 ; https://arxiv.org/pdf/1804.02096.pdf) the authors realize such a solution. They use two ultralow-field NMR resonances produced by a $^{13}CH_3$ group in acetonitrile (CH_3CN) as the two measurements of magnetic fields. In simple words, the interaction between a helium nuclei and a carbon nuclei in acetonitrile provides two two

measurements of magnetic fields. Why there are two different resonances in a single molecule, i.e. how the interaction between helium and carbon nuclei gives two measurements of magnetic field? The trick is related to rules governing how the angular momenta of nuclear spins can be added together. The three spin-1/2 ^1H nuclei in acetonitrile (the same three that appears in the symbol CH_3CN), can add up to a total angular momentum of value 1/2 or 3/2. When coupled to a ^{13}C nucleus, these two different configurations give rise to two different resonances in the spectrum of acetonitrile. Then when magnetic fields are applied, each resonance splits with a different field dependence, allowing for operation as a comagnetometer.

Unlike in previous two-component comagnetometers, the different spin configurations of acetonitrile have identical thermodynamic properties, so there are no spatial separation between the two types of spin that interact with the magnetic field. As a result, in our system systematic errors related to magnetic field gradients are highly suppressed compared to state of the art common devices. This fact boosts the sensitivity of our devise to residual magnetic interactions (Figure 1).

Having the comagnetometer, the authors measure the spectrum of acetonitrile and precisely determine the separations between peaks of its J-couplings frequencies while changing the magnetic field; they compare the results to the interaction of two types of atoms to quantify the improvement in accuracy of the measurement. Last, they demonstrate the achievable sensitivity for a measurement of the spin-gravity coupling with our device.

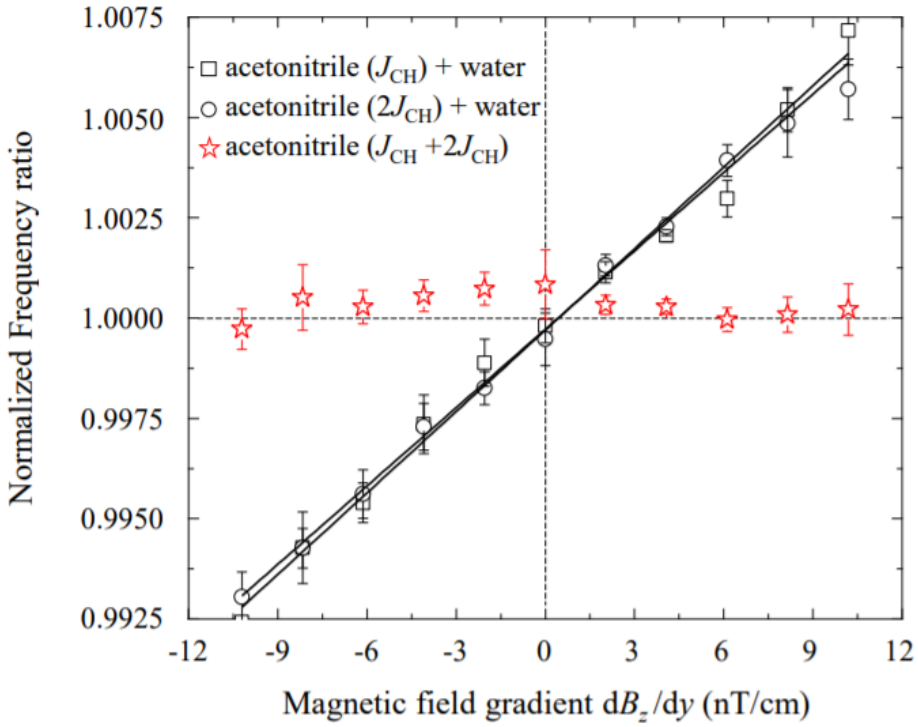

Figure 1: The ratio of multiples splitting $\Delta\nu_2/\Delta\nu_1$ in the spectra of acetonitrile as a function of magnetic field gradient. In red - measurements with our system, with one molecular species in the comagnetometer. In black - measurements with two molecular species. Ideally, the ratio that appears in the vertical axis should not have large dependence on the gradient of the magnetic fields. The graph shows that our results are much less influenced by the gradient than two-species-magnetometers. Taken from Figure 3 in (Phys. Rev. Lett. 121, 023202, 2018 ; https://arxiv.org/pdf/1804.02096.pdf).

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