Forecast:
Susceptible to chilling

The Relaxation Times

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Condensed Matter Physics:
Magnetic Susceptibility vs. Temperature

We hope you've already heard of TeachSpin's contribution toward increasing the prominence of condensed-matter physics (CMP) in the advanced laboratory. Our previous newsletter at http://www.teachspin.com/what-s-new-.html gave an overview of the program we've been working on, which now provides not just an experiment, but the foundational infrastructure for a whole *family* of experiments, bringing condensed-matter phenomena into students' hands. This newsletter takes up just one of that new family of experiments, showing how the TeachSpin CMP dewar system can be used to measure the **magnetic susceptibility** of a huge range of materials, over a working temperature range of 80 – 350 K. Our initial CMP offerings also include experiments in **electrical transport** and in **specific heat**, but these will get their own detailed coverage in future newsletters.

We took up the measurement of magnetic susceptibility because it is applicable to a wide range of materials, and because it measures a property that gets right down to *quantum physics*. Classical theory is unable to account for magnetism at all (according to the Bohr ─ van Leeuwen theorem), but rather simple quantum-mechanical derivations can predict the dia- and para-magnetism of atoms or materials containing them. In fact we've previously introduced our **Foundational Magnetic Susceptibility** apparatus, which can measure magnetic susceptibility χ absolutely, though with fixed sensitivity and only at room temperature. For the simplest paramagnetic systems, absolute susceptibility is a very direct measure of the number of unpaired electron spins in a molecule, and hence a genuine test of the 'Aufbau Principle' of filling energy shells with electrons in atoms and ions.

Now in our new offering we take up the *dependence of the susceptibility χ on the absolute temperature T.* The simplest theory predicts Curie-Law paramagnetism, in which $\chi \propto 1/T$, but there are departures from this prediction arising from many forms of co-operative behavior. Our technique is applicable to any sample, whether solid, or a powder that can be cast into a 6-mm ∅ × 25-mm long cylinder. The technique is sensitive enough to easily detect the diamagnetism of our preferred 'binder' for samples, namely epoxy resin. Measurements on epoxy 'blanks' permit a correction for the epoxy-component of other samples. The method we chose for measuring χ for all these samples is sometimes called a 'Hartshorn-coil' or 'a.c. susceptibility' method, and it's all done electronically, with the sample in a controlled-temperature and 1-atmosphere environment.

Fig. 1: The Hartshorn coil for measuring magnetic susceptibility, mounted on the temperature-controlled baseplate of the TeachSpin CMP dewar (shown with inner and outer vacuum cans removed, and with the dewar inverted).

Here's how it works. Inside a long solenoid, acting as a 'primary coil', an alternating current of known amplitude produces a spatially uniform *H*-field, sinusoidal in time. Inside that solenoid, we arrange for a long(ish) cylindrical sample to lie inside a short(ish) secondary coil, so that the sample acts like the core of a transformer. Inside the sample, the magnetic field is given by

$$B = \mu_0 (H + M) = \mu_0 (H + \chi H)$$

by the definition of the magnetic susceptibility χ. The emf induced in the secondary coil is then proportional to $dB/dt \propto (1+\chi)\, dH/dt$, and this emf is what we measure.

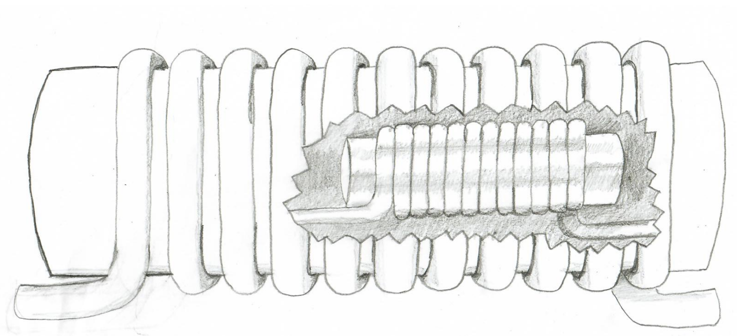

Fig. 2: A sketch, not to scale, showing the topology of an outer (primary) solenoid, with a cutaway depicting one of the inner (secondary) coils, with a cylindrical sample inside it.

Since $\chi << 1$ for typical samples, we isolate the small but interesting part of the $(1+\chi)$ term by arranging a duplicate secondary coil also to lie inside the primary coil — but this one *not* containing the sample. The emf induced in this 'empty' coil will be proportional to $(1+0)\, dH/dt$ instead. Now with those two secondary coils connected in anti-series, we get a net a.c. emf proportional to $\chi\, dH/dt$. When the primary coil is driven by a sinusoidal current, this predicts a secondary-coil emf that is also sinusoidal, with the same frequency as the drive, but phase-shifted by 90° relative to it — and with an amplitude directly proportional to the susceptibility χ. A lock-in amplifier is ideally suited to the sensitive, and selective, detection of such a sinusoidal signal, occuring as it does with a known frequency and phase.

In keeping with the TeachSpin philosophy, we wanted students to be able to see 'where the rabbit gets into the hat', so we have arranged that a sample with a large susceptibility, such as a ferrite bead, can be inserted to give signals that are directly visible on an oscilloscope -- no lock-in yet required. Figure 3 shows a view of the signals monitoring the primary current and the net secondary-coil emf, in such a case.

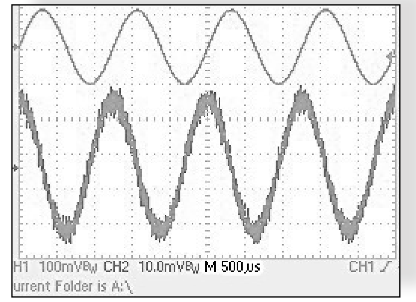

Fig. 3: (Upper trace) A monitor-voltage waveform proportional to the current *i(t)* in the primary coil; (lower trace) The net emf from the anti-series-connected secondary coils, when a ferrite-bead sample is centered inside one of the secondaries.

Typical numbers here are a primary current of amplitude 100 mA at 793 Hz, generating an *H*-field of amplitude 800 A/m (equivalent to *B* of 1.0 mT or 10 gauss, or *H* = 10 Oe in cgs units). Under these conditions, the ferrite-bead sample gives a signal of the same frequency, 90° shifted in phase, of amplitude about 19 mV. A signal like this is not only 'scope-visible, but it also enables students to get the lock-in detection method properly adjusted for phase.

Even a weakly-diamagnetic material, such as an all-epoxy 'blank' sample, gives a signal readily detected. In Fig. 4 below, the magnitude of the oscillating magnetic moment is about 6×10^{-9} A·m^2 (or 6×10^{-6} emu, in cgs notation). Yet it is still detected with good signal-to-noise ratio, even using a lock-in time constant as small as $\tau = 0.3$ s.

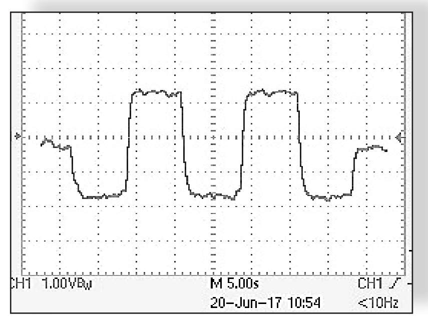

Fig. 4: The dc output of the lock-in amplifier, proportional to the amplitude of the net secondary voltage. The three levels or steps correspond to positioning the sample remote from both secondaries, centered in one secondary, and centered in the other secondary. The sample, an all-epoxy 'blank', gives an a.c. emf of rms measure about 1 µV at the lock-in's input.

The final 'independent variable' being exercised in the graph above is to use the sample-holder rod to make a manual re-adjustment of the sample's position relative to the (two) secondary coils. Relative to a zero-level when the sample lies in neither secondary, one gets a positive output for its presence in one secondary, and a negative output for its presence in the other.

A sample containing about half a gram of a paramagnetic salt gives signals of similarly low noise level, but with signal level of order *hundred-fold larger*. What's more, as the temperature is lowered, signals from paramagnetic samples grow, while competing Johnson noise from the secondary coils shrinks, so the S/N only *improves* at lower temperatures.

Our CMP dewar comes with everything needed to servo-control the temperature of the 'baseplate' on which the Hartshorn-coil apparatus is mounted. Our coil form is built of solid alumina (Al_2O_3), chosen for its superb thermal conductivity. Thus our sample is surround by an isothermal alumina sleeve, whose temperature can be measured in real time. The sample takes on the temperature of this sleeve via casual mechanical contact, and by immersion in nitrogen exchange gas at 1-atmosphere pressure.

Clearly this makes possible the (relative) measurement of $\chi(T)$, and the Figures below display some results. Each plot shown represents a 'run' which takes about an hour of cool-down time, followed by a few hours' data-taking 'on the way up' in temperature. It's easy to find samples showing pure Curie-Law behavior over the accessible 80-350 K range, but there are plenty of exceptions. The gadolinium-oxide data in Fig. 5 has been overlaid with a model Curie-Weiss law $\chi(T) = C/(T-\theta)$, with θ = -14 K.

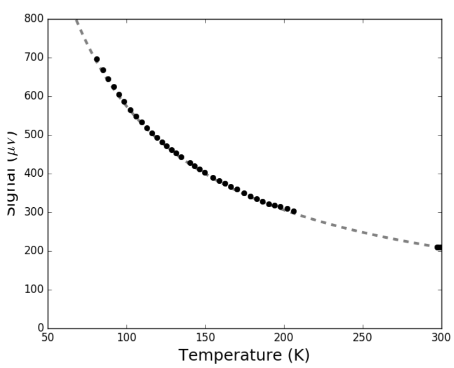

Fig. 5: A relative measure of the susceptibility signal from a gadolinium-oxide [Gd_2O_3] sample, as a function of absolute temperature *T*. The vertical scale gives the rms measure of the a.c. signal at the lock-in's input.

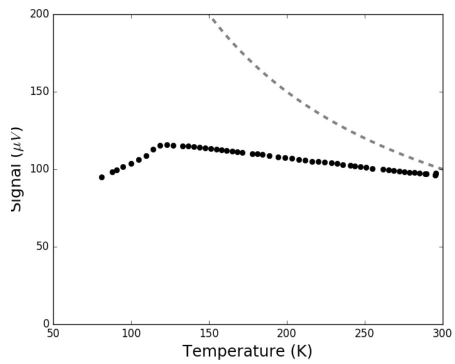

Fig. 6: Susceptibility signal vs. absolute temperature for a manganese-monoxide [MnO] sample. The dashed curve shows a 1/*T*-dependence that does *not* fit the data, either above or below 120 K.

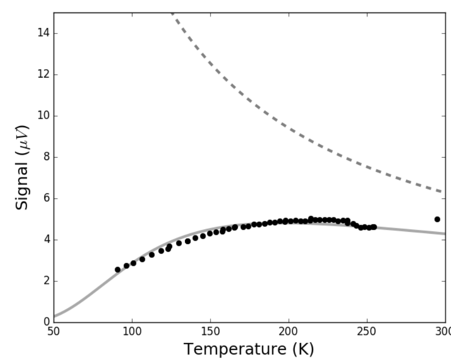

Fig. 7: Susceptibility signal vs. absolute temperature from a copper-acetate [$Cu_2(CH_3COO)_4 \cdot 2H_2O$] sample. The solid curve shows the results of a copper-dimer model of two interacting spin-1/2 atoms.

The manganese-monoxide data in Fig. 6 has χ rising much less rapidly than 1/*T* upon cooling, and also shows a discontinuity in slope near 120 K, attributed to the onset of antiferromagnetic ordering.

Finally, the copper-acetate data in Fig. 7 displays the sensitive detection of markedly weaker signals. It indicates χ-values that scarcely rise at all upon cooling, and then fall toward zero values near 50 K, behavior attributed to copper-atom dimers settling into a (diamagnetic) spin-singlet state at low temperatures.

Our Magnetic Susceptibility package includes a dozen prepared samples. It also comes with all that's required for students to prepare their own samples by a simple epoxy-casting method. Of course it also has a complete Manual, with details of the theory of magnetic susceptibility, the behavior of the apparatus, and methods for data reduction. We have more coverage of the package contents at our website www.teachspin.com.

So here's what you'd need. Building on the foundation of our CMP dewar, with its vacuum system, and its temperature measurement and control electronics, you'd need to add our CMP-MS package. This includes the Hartshorn-coil system, the coil-driver electronics, the set of prepared samples and a sample-making kit, and other accessories. You also need a basic lock-in amplifier; and we further suggest you consider our Foundational Magnetic Susceptibility apparatus for an orientation to magnetism, and the absolute calibration it enables. The payoff of this suite of apparatus is a genuine introduction to magnetic measurements: a sensitive method for exploring the spin content of molecules, and the cooperative behavior of magnetic moments in condensed-matter spin systems.

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Featuring – **Magnetic Susceptibility**
measured in the TeachSpin CMP

You'll have a chance to visit the 'Food Truck' at the
AAPT Summer Meeting
July 23-25, 2017 in Cincinnati
Barbara and Jonathan will be there to show you around! Don't miss this opportunity. See you there!

TeachSpin's

'Food Truck for the Physics Mind'

TeachSpin's 'Food Truck for the Physics Mind' is also due to be on display at the fall meeting of the New England section of the APS, on October 20-21, 2017.

APS

We will have that 44-Foot trailer on the road, **making visits to schools in New England during the month of October.** Schedule your visit, at no cost to you, by contacting Sue Leigh at our office at 716-885-4701.