Forecast:
To "Be" varied

The Relaxation Times

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VOL.VI NO. 1 *NEWSLETTER OF TEACHSPIN, INC.* *November 2022*

Foundational (Magnetic)^2 Susceptibility

What's with the squaring, the exponent-2, in the title of our Foundational Magnetic Susceptibility (FMS) experiment? The answer is, we're offering an enhancement to past and future users of this apparatus. You'll see the power-2 law below; but in this Newsletter about FMS we would also like to emphasize two more general points:

- First, TeachSpin welcomes customer feedback, and can respond to their bright ideas; and
- Second, we always love to give students a *new independent variable* to exercise in any of our physics experiments.

Let's start with a reminder of what our FMS experiment does: It allows students to measure the magnetic susceptibility (χ) of any liquid, solid, or powdered material; it *unambiguously* provides the sign, as well as the magnitude, of χ. The operation of FMS can be modelled from first principles, so that it gives χ-values without any reference to 'accepted values' or calibration samples. The apparatus is so easy to use that it doesn't even require an oscilloscope, much less a computer, for its operation.

The apparatus employs the Guoy method, in which the sample takes the form of a vertically-extended 'log' of material of uniform cross-sectional area A, and subjects one end of that 'log' to a strong field B (while the other end lies in a near-zero field). Under these circumstances, there is an extra force of the magnet on the sample, given by

$$\Delta m \cdot g = F_z = \chi A \frac{B^2}{2\mu_0} \quad .$$

Note the claimed B^2-dependence of the force on the field B -- that's the exponent-2 we're talking about. In a traditional Guoy-susceptibility apparatus, B is provided by a heavy floor-mounted electromagnet, while the sample is suspended by a balance, and the F_z manifests itself by a change in the apparent mass of the sample. In our FMS set-up, we measure the 3rd-Law *companion force,* the force of the *sample on the magnet*, seeing the same Δm as a change in the apparent mass of the magnet. We detect that Δm by 'weighing the magnet'; this works because the (permanent) magnet needs no wires, no cooling water, no connections at all. Our balance has a capacity of 200 g to accommodate the modest mass of the magnet-structure, and its resolution of 0.001 g provides enough sensitivity to detect magnetic susceptibilities even as small as that of liquid water.

But while this design does allow absolute measurement of the susceptibility χ, it does not provide a method for *varying* the B-value to confirm that B^2-dependence. So we were happy to entertain a question from FMS user Dr. Zoe Boekelheide of Lafayette College (see sidebar) about whether we could devise a method to turn the B-value into an independent variable, one under students' control.

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Zoe Boekelheide is an Associate Professor in the Physics Department at Lafayette College, a liberal arts and engineering college in Easton, PA. She teaches at all levels of the undergraduate curriculum, including introductory and advanced laboratory courses. Her research interests lie in magnetism and magnetic materials, in particular antiferromagnetic thin films and ferro- and ferrimagnetic nanoparticles. She reports "I have used TeachSpin's Foundational Magnetic Susceptibility experiment as the first experiment in our Advanced Physics Laboratory course because it is an opportunity to teach good safety and material handling practices, finding literature values of material properties, tricky electromagnetic unit conversion, and propagation of error from multiple sources. It also exercises the advanced electromagnetism and magnetism-in-materials understanding that students have recently mastered at this level."

"As a magnetician, most of the interesting materials I work with are nonlinear and don't have a single well-defined susceptibility. I was looking for a way for students to be able to test the assumption of linearity in the FMS apparatus, and contacted TeachSpin with the idea of using multiple magnet strengths."

We at TeachSpin thank Dr. Boekelheide not only with this Newsletter acknowledgement, but also with a complimentary set of the newly-produced extra magnets. What ideas do you have for a TeachSpin experiment?

We thought about mechanical arrangements that might allow a continuous variation of B, but settled on a simpler solution. We are now offering a set of three extra magnet-structures, crafted to add three new B-values to the one (near 0.4 Tesla) provided by our original magnet. Since the original magnet has its steel yoke coated in a silvery nickel-plating, we imaginatively had the yokes for our three new magnets powder-coated in colors of black, white, and red.

We designed the new magnets to offer two smaller, and one larger, B-value as compared to the original magnet. And we're not telling students those values; they're going to *measure* them, using the same $\boldsymbol{iL} \times \boldsymbol{B}$ method that we built into the original FMS experiment. So now any of our existing FMS users can order this set of new magnets, which are compatible with all the FMS units we've manufactured. The set will come with a new Appendix for the FMS Manual, describing the motivation and the methods for the new experiments they make possible.

Here's a bit of theory that shows one way of understanding why there should be a B^2-dependence in the force that's experimentally detectable. We choose a 'virtual work' method of understanding why the magnetic force arises in the Guoy geometry. Consider a log-like sample with its bottom end in the maximum-field region at the center of a magnet-assembly, and with its top end in a region of negligible field. Each slab of the log, of area A and height δz, represents a volume $\Delta V = A\ \delta z$ of magnetic material. Now the energy density of magnetic fields is $u_B = \boldsymbol{B}\bullet\boldsymbol{H}/2$, and given the definition of $\boldsymbol{H}$, this can be written as

$$u_B = \frac{1}{2}\boldsymbol{B}\cdot\boldsymbol{H} = \frac{B^2}{2\mu_0} - \frac{1}{2}\boldsymbol{B}\cdot\boldsymbol{M} \quad .$$

We notice a first term matching the energy-density of a B-field in vacuum, and a second term which gives the extra energy due to the presence of a material sample. For materials described by a susceptibility χ, we have magnetization $\boldsymbol{M} = \chi\ \boldsymbol{H}$; for isotropic materials with $|\chi| << 1$, we have $\boldsymbol{M} \approx \chi\ \boldsymbol{B}/\mu_0$. Now for a sample of volume ΔV, the change δu_B in energy-density translates to an increment of magnetic energy,

$$\delta U_{mag} = \Delta V\ \delta u_B = -\frac{1}{2}B\cdot\frac{\chi B}{\mu_0}\ \Delta V = -\frac{B^2}{2\mu_0}\chi\ \Delta V = -\frac{B^2}{2\mu_0}\chi\ A\ \delta z$$

Notice that a B^2-dependence has emerged. Note also that a more-positive susceptibility stands for a lower system energy. Now in our sample geometry, consider a log of sample that moves downward, by a virtual displacement δz. Apart from the bottom and top slices of sample, every location-in-z has the same conditions before and after, assuming that the log-of-sample is uniform over its height. The effect of the virtual displacement is just as if a slab of height δz had been removed from the top (where the field, and hence the magnetic energy, are assumed to be negligible), and a slab of height δz had been added at the bottom (where it contributes an energy-change given by δU_{mag} above).

The system now has lower energy, and that's because it's done virtual work δW, pulling the sample downward by δz. But work per unit distance means there's a (downward) force of the magnet on the sample, and the force F_z is given by $\delta W = F_z\ \delta z$. This gives the desired result, the same F_z expression as quoted above. This derivation also reveals that the Guoy method is insensitive to the details of how $\boldsymbol{B} = \boldsymbol{B}(z)$ depends on height z. That's why in our experiment, students do *not* need to measure the field profile or the field gradient, just the value of B at the 'sweet spot' of maximal field at the center of the magnet.

Hence to confirm a B^2-dependence using FMS data is to confirm that magnetic energy really is a *quadratic function of field,* something derived in theory courses but rarely subjected to any direct experimental test.

Naturally we wanted to test the performance of our new magnets, so we measured the B-values at the center of all four of them, using the 'current-hairpin' method that comes with the FMS equipment. The results give the locations of the four data-points along the B-axes in the graphs shown. [Incidentally, we also measured those four field-values using our TeachSpin 1-Tesla Hall probe, itself calibrated against magnets measured by NMR methods. We found the $\boldsymbol{iL} \times \boldsymbol{B}$ results and the Hall-probe results differed by 0.3 ± 0.7%, confirming that within FMS we really can measure field-strengths to better than 1% precision and accuracy.]

Using these now-calibrated magnets, we measured the apparent mass-change Δm emerging as the magnets interacted with our favorite paramagnetic sample, gadolinium oxide (Gd_2O_3). First results are shown in Fig. 1, where we plot Δm as a function of B, against a parabola depicting B^2 behavior.

Alternatively, we can plot Δm as a function of B on log-log scales in Fig. 2, where the straight-line fit depicts power-law behavior, and the slope gives us a power-law exponent of 2.01 ± 0.04.

[Thanks go to TeachSpin summer-2022 intern Calvin Besch for taking the data shown here.]

So the method works! And with these new capabilities, we leave to your students to answer, *by their own hands-on experiments,* some other questions:

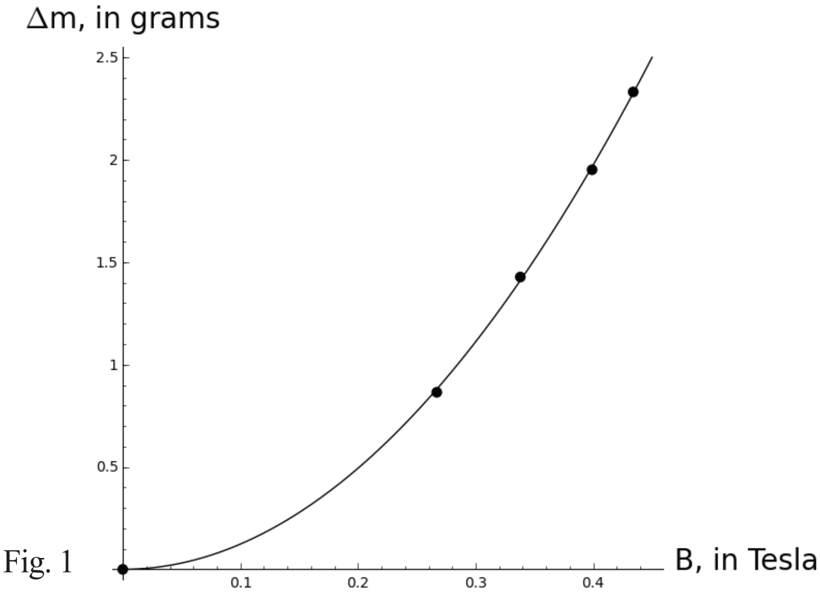

Fig. 1

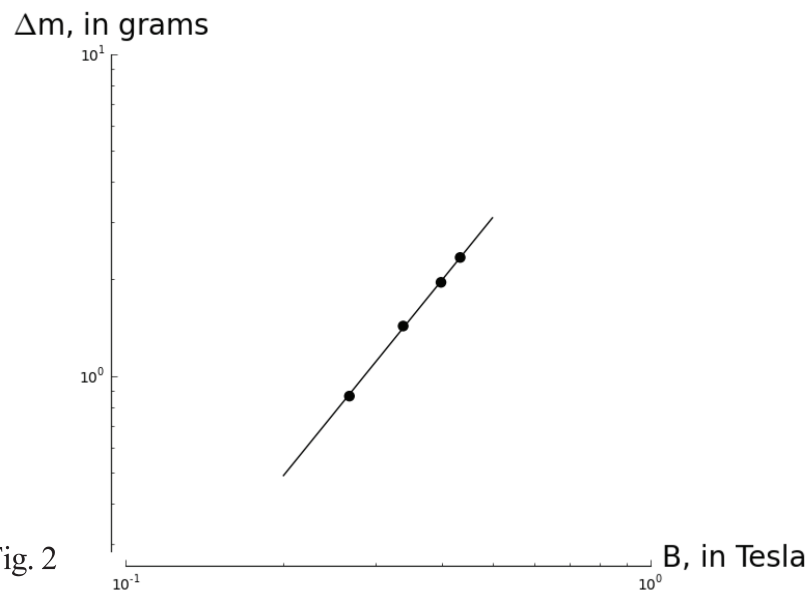

Fig. 2

- Does this B^2-dependence work for paramagnets of χ-values differing from that of Gd_2O_3? The samples that come with FMS include materials of both larger, and smaller, χ-values.
- Does this B^2-dependence work for diamagnets ($\chi < 0$) just like it does for paramagnets? There are two strongly-diamagnetic materials in the FMS sample-set for this test.
- Finally, does this B^2-dependence work for all samples? There are two ferromagnetic samples (cobalt wire and ferrite powder) in our sample-set, and such samples are subject to saturation: the dependence of M on H might differ from the simple linearity of $M = \chi H$ with χ constant. If M is subject to saturation, the observable Δm in our new FMS experiment might rise not as B^2, but as B to some other (and lower) power.

We've currently priced the added set of three magnets, plus supplement to the Manual, at $295, and we're ready to ship magnet-sets to owners of FMS. We'll also be including the three extra magnets in the 'premium version' of FMS that's now listed in our full price list – see our webpage at **www.teachspin/prices** and try the detailed-pricing tabs.

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