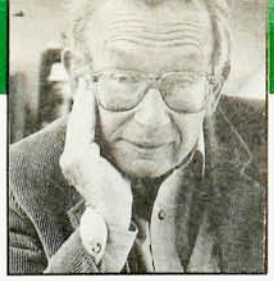


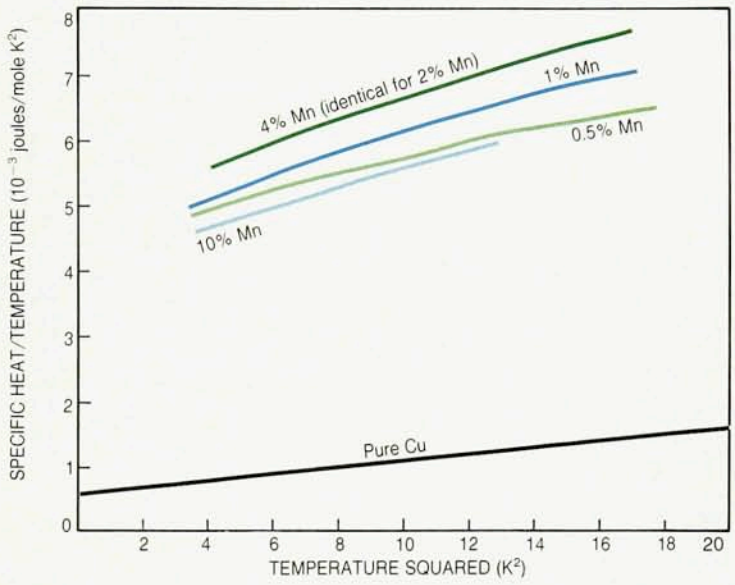
SPIN GLASS I: A SCALING LAW RESCUED

Philip W. Anderson

The history of spin glass may be the best example I know of the dictum that a real scientific mystery is worth pursuing to the ends of the Earth for its own sake, independently of any obvious practical importance or intellectual glamour. If a phenomenon seems likely to contradict the fundamental principles you thought you understood (that's what I mean by a *real* mystery—so long as you also believe the experiments!) you should stick with the phenomenon. This fundamental dictum of good science is increasingly neglected by our masters who provide the money; spin glass is even less popular with them than superconducting materials were before 1987. The pursuit of the spin glass mystery led, *inter alia* and aside from all the good solid-state physics that resulted, to new algorithms for computer optimization, a new statistical mechanics, a new view of protein structure, a new view of evolution and new ideas in neuroscience.

But it all started with some very simple physics. Measuring magnetic resonance and magnetic properties of dilute magnetic ions in insulators (such as Mn in ZnO) to probe magnetic interactions was a very useful game played in the 1950s and early 1960s by John Owen, among others. At about the same time, he and the Berkeley magnetic resonance group of Arthur Kip, Walter Knight, Charles Kittel and others tried diluting manganese into the nonmagnetic metal copper to test the proposed Ruderman–Kittel–Kasuya–Yosida interaction between spins via free electrons, and to see whether the free electrons' exchange interaction with the magnetic ions affected their resonance behavior—that is, to see if there was an electron magnetic resonance equivalent to the nmr Knight shift and the Korringa free-electron relaxation of nuclei.

Philip Anderson is a condensed matter theorist whose work has also had impact on field theory, astrophysics, computer science and biology. He is Joseph Henry Professor of Physics at Princeton University.



Specific heat of Cu–Mn alloys at low temperatures is independent of the manganese concentration, and it varies linearly with temperature when the contribution due to pure copper is subtracted. In the range of manganese concentrations shown here, the low-temperature properties of the alloy are dominated by the interaction between magnetic moments on manganese atoms, which leads to the spin glass behavior. (Adapted from J. E. Zimmerman, F. E. Hoare, *J. Phys. Chem. Solids* **17**, 52, 1960.)

This simple set of experiments opened up at least two cans of worms. The physics of the effect of the free electrons on the individual Mn ions is, of course, closely related to the Kondo problem and the Anderson model, but this is not our worm-receptacle of choice. We are interested in what they saw when the samples contained 0.1–10% manganese and the behavior was dominated by the ion–ion interactions.

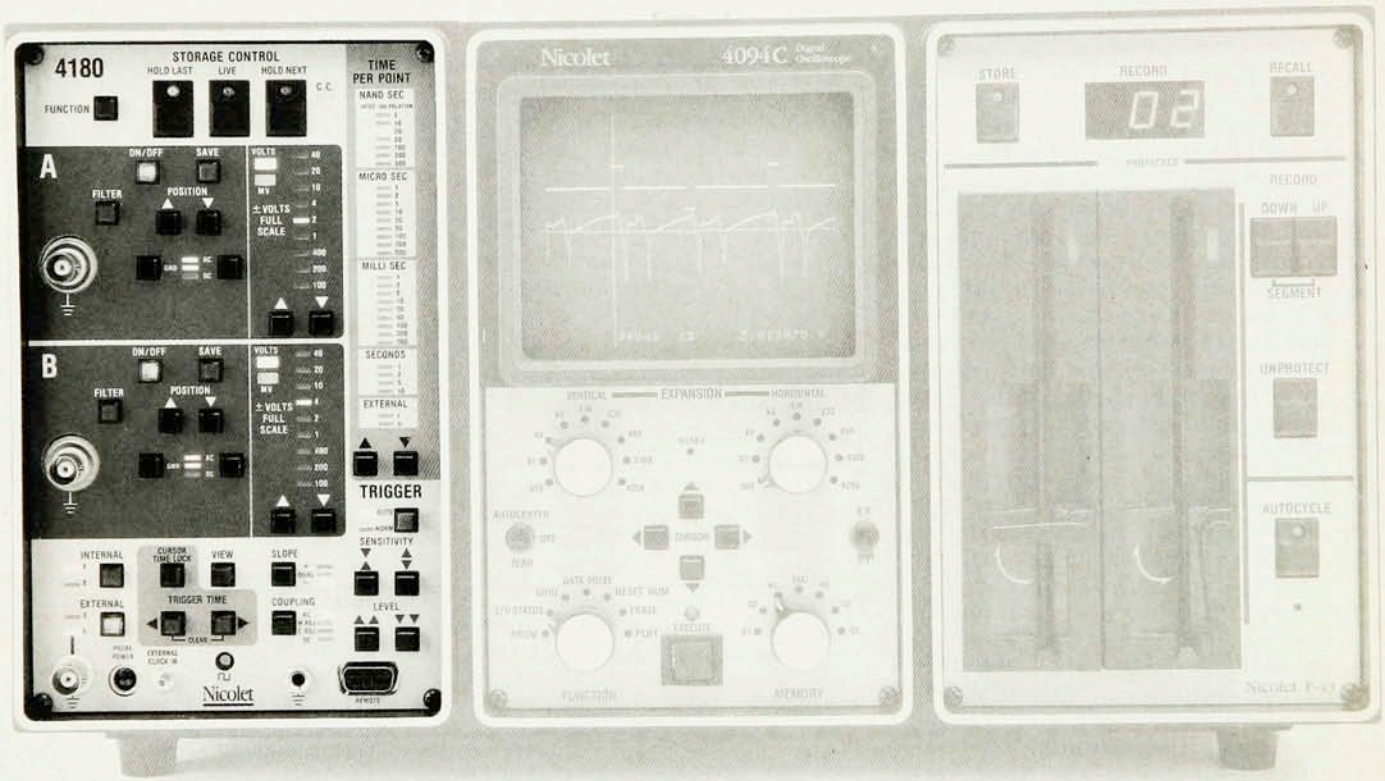
The magnetic resonance effects were not very instructive at the time, involving complicated physics that was actually one of the last areas to be clarified. I will discuss this physics in a later column. What first attracted attention were simple thermodynamic measurements such as those of magnetic susceptibility and specific heat.

The extra specific heat at low temperature was perfectly linear in T, with a slope about five times that of the background copper, independently of concentration, but then the extra specific heat peaked at a concentration-dependent temperature T_0 and dropped down at a rate one could imagine to be approximately $1/T^2$. (See the figure above.) The susceptibility χ rose from a constant value to an (apparently) broad peak near T_0, then fell off at a good approximation to the Curie law $\chi = C/T$ (C is the Curie constant) with the right Bohr magneton number for Mn^{++} with its $g = 2$, $S = {}^5/_2$ ground state.

After a bit of to-ing and fro-ing, a

The New 4180 Plug-In

SPEED TRIALS.



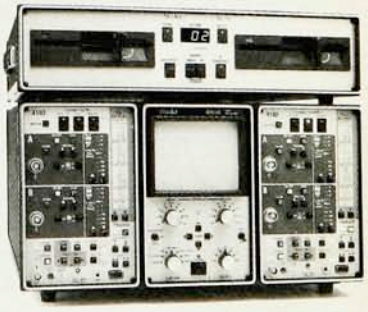
- ***Multi-channel: two or four channel configurations.***
- ***Unmatched single-shot capabilities.***
- ***High speed, 200 MHz digitizing.***
- ***100 MHz analog input bandwidth.***
- ***Real-time math functions.***

- ***For your Free Speed Trial call: 800-356-3090 or 608-273-5008***

Nicolet Test Instruments Division
P.O. Box 4288
5225-2 Verona Road
Madison, WI 53711-0288

Nicolet Digital Oscilloscopes

Speed. Using the latest designs in ADC technology, your input signal can be digitized at speeds up to 200 MHz (5ns per data point) and saved for analysis. The wide band input amplifiers allow signals up to the 100 MHz Nyquist limit to be input without distortion. Sophisticated trigger setup displays allow you to accurately set the level, sensitivity, and slope to make one-shot transients easy to catch; eliminating the usual hit or miss guesswork. For multi-channel applications two 4180's can operate together in one mainframe producing a four channel scope with no degradation in speed or performance.



Real-Time Math. In addition to the extensive post-processing capabilities in the mainframe, the 4180 has several useful routines which present computed results as live, real-time displays: *FFT, MAX/MIN, A+B, A−B, A×B, A/B,* and *AVERAGING.*

Nicolet

INSTRUMENTS OF DISCOVERY

group at Grenoble showed that for these "classic spin glasses" (as they much later came to be known) all of these data fit onto a single universal curve with the temperature, energy and entropy scales all linearly proportional to concentration. We know now that this is a good confirmation of the extraordinarily simple underlying physics—that the dominant term in the Hamiltonian for the magnetic moments of solute atoms is the RKKY exchange integrals

$$J(r_{ij}) = J_0 \frac{1}{r^3} \cos(2k_F r_{ij})$$

where k_F is the Fermi momentum. These RKKY exchange integrals fall off slowly with distance and alternate in sign.

In these random, dilute solutions this behavior has the effect of randomizing the exchange integrals (since $1/(2k_F)$ is less than an interatomic distance) and each spin sees quite a few neighbors with each of which it has an exchange interaction that is random in both sign and magnitude. The probability distribution of these exchanges has a scale proportional to $\langle 1/r^3 \rangle_{avg}$, which is in turn equal to the density of solute atoms. The form of the probability distribution, however, is independent of the density except for the scale.

A 1987 postscript to this story was written by Michael Stephen and Elihu Abrahams. The long-range $\cos(2k_F r)/r^3$ form occurs because of the sharp drop in occupation of free-electron states at k_F. Pierre-Gilles de Gennes had proposed, long before, that scattering of the free electrons by impurities reduced the range of this effect by a factor $\exp(-r/l)$, where l is the mean free path of the electrons, by dephasing the electronic wavefunctions at the Fermi surface; this unfortunately would ruin the scaling law for the probability distribution of the interaction. Until recently this argument was universally accepted, but it turns out not to be true, as Stephen and Abrahams have shown: The distribution is almost unchanged by scattering, because scattering merely shifts the phases of the wavefunctions near the Fermi surface without changing their relative phases in any given sample. This is a vital key to the properties of real spin glasses, and in addition restores the scaling laws.

But, as you'll see in my subsequent columns, aside from the scaling law (which has only just been rescued) none of the features of these measurements were to be understood for another 20 years or more, and the real physics is still a problem. ■