

by the in-plane boron p orbitals.

Although they contribute neither phonons nor charge carriers to the BCS coupling, the magnesium atoms play a key role. By donating their two valence electrons to the boron atoms, the magnesium atoms become positively charged and attract electrons. Feeling the strongest attraction are the electrons in the out-of-plane boron p orbitals, which constitute the boron π state. As a result of the attraction, the energy of the π -state electrons is lowered. “And that,” says UC Davis’s Warren Pickett, “is what causes the hole-doping of the σ bands. The attraction lowers the energy of the π bands enough to accept electrons from the σ bands.”

Those holes can be filled by electron doping. Working in Bob Cava’s lab at Princeton University, Joanna Slusky and others investigated the effect of substituting the magnesium with aluminum, which has one more valence electron. At an aluminum content of 10% and higher, superconductivity is suppressed. The Princeton team also found that adding aluminum causes the boron interplane distance to shrink discontinuously. Between aluminum contents of 10% and 25%, a new, more tightly layered phase coexists with the phase that superconducts. Above 25%, the superconducting phase disappears.

That MgB_2 is on the brink of a structural instability could be helpful to its superconductivity. Phase transitions can supply low-energy phonons that boost the electron-phonon coupling. The proximity of the structural phase transition might also explain why superconductivity isn’t found in the other metal diborides: Only mag-

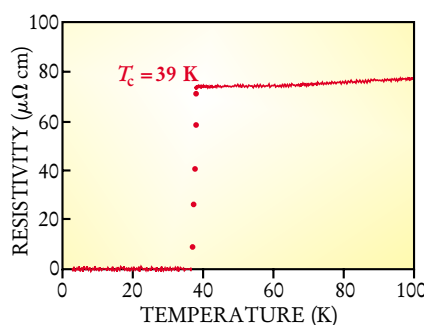


FIGURE 2. SUPERCONDUCTIVITY in magnesium diboride appears at a temperature of 39 K. (Adapted from ref. 1).

nesium has the right combination of size and charge distribution to turn boron into a superconductor.

Overlooked

Condensed matter physicists are amazed that MgB_2 ’s superconductivity went undiscovered for so long. Walther Meissner found several superconducting interstitial compounds of transition metals with borides, carbides, and nitrides in Berlin in the 1930s. Two decades later, John Hulm and Bernd Matthias discovered more superconducting borides—with transition metals—at the University of Chicago. But how did they miss MgB_2 ?

Stanford’s Ted Geballe, who began working on superconductors in the 1950s, speculates that the procedures Hulm and Matthias used probably failed for nontransition elements such as magnesium because they would have made an insulating oxide. Florida State’s Zack Fisk offers an alternative explanation. He points out that Matthias made his compounds in an arc furnace. If magnesium isn’t con-

fined under pressure (hard to do in an arc furnace), it evaporates long before it reaches boron’s rather high melting temperature.

Clearly, as figure 2 shows, Akimitsu didn’t miss MgB_2 ’s superconductivity—but not because he was deliberately looking for it. Hoping to find a new superconducting system, he and his team were investigating ternary compounds of magnesium, boron, plus a transition metal, such as titanium or vanadium. As they reduced the proportion of magnetic atoms, they found that the compounds’ superconducting properties improved, with the best performance coming from the compound that completely lacked transition metal ions.

It’s too early to say whether materials based on MgB_2 will be technologically useful. But one step in that direction has already been taken. The Iowa State group has made dense superconducting wires out of the compound.⁷

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Have We Glimpsed ‘New Physics’ in the Muon’s Anomalous Magnetic Moment?

The anomalous magnetic moments of the electron and its heavier sibling, the muon, can be measured with exquisite precision. And they are unique probes of fundamental physics. The electron’s anomalous magnetic moment (a_e), known to 4 parts per billion, provides by far the best determination we have of the fine-structure constant α . (See PHYSICS TODAY, March 2001, page 29.) The muon’s anomalous magnetic moment (a_μ), though not quite so spectacularly measured, is in fact a more sensitive probe of putative “new physics” beyond the standard model of elementary particle interactions.

A $g - 2$ measurement at Brookhaven’s muon storage ring shows a small but tantalizing disagreement with the standard model.

That’s essentially because m_μ , the mass of the muon, is about 200 times the electron’s mass.

Hence the cautious excitement in February, when the international Muon ($g - 2$) Collaboration announced the latest results from its experiment (see figure 1) at the Brookhaven National Laboratory. The completed analysis of its 1999 data, the group reported, had shrunk the

uncertainty of its a_μ measurement enough to show a tantalizing but still tentative disagreement with the standard-model prediction.¹ At this point, the measured a_μ , with an uncertainty of 1.3 parts per million, is 2.6 standard deviations larger than the calculated theoretical value.²

Is this a harbinger of new physics? “We’ll know better when the analysis of our 2000 and 2001 data has brought our experimental error down by about another factor of 3,” says collaboration co-spokesman Lee Roberts (Boston University). The other spokesman is Vernon Hughes (Yale), who set this ambitious undertaking in motion



FIGURE 1. STORAGE RING of the Muon ($g - 2$) Collaboration's experiment at Brookhaven. An iron-core superconducting magnet provides the very stable and uniform 1.45-T field that keeps the 3.1-GeV muons circulating through the ring's 9-cm-diameter vacuum pipe.

almost 20 years ago.³

Experiments of this kind are called “ $g - 2$ ” measurements because they measure directly the small difference between the Landé g factor of the lepton's gyromagnetic ratio and 2, the value ascribed to the electron's (and the muon's) g by the Dirac equation in the absence of field-theoretic corrections. The muon's “anomalous” magnetic moment

$$a_\mu \equiv (g_\mu - 2)/2$$

is measured by observing the small difference between its cyclotron frequency ω_c and its spin precession frequency ω_s in a magnetic field. In a vertical field B , the muon's intrinsic spin precesses around the field direction as the particle executes cyclotron orbits in the horizontal plane. If g_μ were precisely 2, the precessing spin of a muon longitudinally polarized (parallel to the momentum) at the start would remain perfectly aligned with its circling momentum. Any observed difference $\omega_a \equiv \omega_s - \omega_c$ between the two angular frequencies implies an anomalous magnetic moment

$$a_\mu = \omega_a m_\mu c / eB.$$

Beyond the Dirac equation

An early triumph of quantum electrodynamics was Julian Schwinger's 1948 calculation of the first-order radiative correction to the naïve Dirac magnetic moment of the electron. The radiation and re-absorption of a single virtual photon, he pointed out, would contribute an anomalous magnetic moment of

$$a_e = \alpha/2\pi \approx 0.00116.$$

This leading QED correction term (figure 2a) is the same for both electrons and muons. But higher-order QED radiative corrections are, in gen-

eral, bigger for the more massive muon. Nowadays theorists go beyond QED to include standard-model corrections involving the radiation of virtual hadrons (figure 2b) and neutrinos and weak vector bosons (figure 2c). With such effects included, the current standard-model prediction for the muon's anomalous magnetic moment is

$$a_\mu = 116\,591\,597 \pm 67 \times 10^{-11},$$

which is $426 \pm 165 \times 10^{-11}$ less than the world experimental average, dominated by the new Brookhaven measurement.

Veteran particle-physics bump hunters rightly wary of spurious enhancements should keep in mind that a 2.6-standard-deviation departure from an explicit prediction is statistically more significant than such an enhancement in some random bin of a histogram.

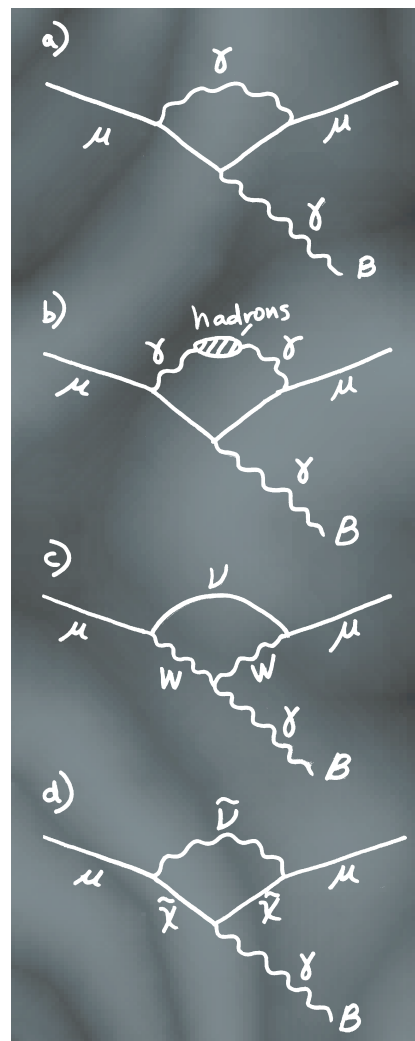
Beyond the standard model

Assuming, for the moment, that it's

FIGURE 2. FEYNMAN DIAGRAMS representing processes contributing to the muon's anomalous magnetic moment. In each diagram, the bottom photon represents coupling to the external magnetic field B . The first three are standard-model contributions: (a) A single virtual-photon loop gives the leading QED term. (b) Virtual hadron pairs contribute to vacuum polarization. (c) A loop with virtual W bosons and a neutrino contributes to electroweak radiative corrections. (d) Beyond the standard model, a conjectural contribution involves a sneutrino ($\tilde{\nu}$) loop. The virtual chargino ($\tilde{\chi}$) is a superposition of the supersymmetric partners of the Higgs and W bosons.

not a statistical fluke or an experimental blunder, the first thing a discrepancy of this size suggests is “supersymmetric” effects beyond the standard model.^{2,4} Because the standard model, despite its unbroken record of successes, is manifestly incomplete, particle physicists are urgently seeking glimpses of a more encompassing theory.

Among particle theorists, the most popular such generalization of the standard model is supersymmetry, affectionately called SUSY. The theory posits heavy boson partners (with names like squarks, smuons, and sneutrinos) for all the fundamental fermions, and fermion partners (photinos, gluinos, winos, and higgsinos) for the fundamental vector and



scalar bosons.

For plausible free parameters in the SUSY scheme, the magnitude and sign of the observed Brookhaven discrepancy suggests a mass between 100–450 GeV for the lightest SUSY partners. That's just beyond the mass range that has been scoured, without a find, by experiments at CERN's now defunct LEP electron-positron collider. In this mass range, the largest SUSY contribution to the muon's anomalous magnetic moment is likely to come from the Feynman diagram in figure 2d.

Of course, SUSY is not the only explanation being offered for the apparent excess in a_μ . Theoretical alternatives include internal structure within the muon (which the standard model takes to be a point particle), leptoquark hybrids, or compact extra spacetime dimensions.

There is a more prosaic alternative. The bulk of the quoted uncertainty in the standard-model prediction comes from vacuum-polarization effects due to virtual hadron loops (figure 2b). These hadronic effects cannot be calculated from first principles. They require phenomenological inputs concerning mesonic resonances and hadronic decay modes of the very heavy tau lepton. Perhaps the uncertainty assigned to the standard-model prediction of a_μ is an underestimate and hadronic experiments now in the works at several low-energy e^+e^- colliders around the world might shrink the theory's provocative discrepancy with the Brookhaven $g - 2$ result.²

The experiment

In the mid-1980s, after an impressive $g - 2$ experiment at the CERN Proton Synchrotron (PS) had measured the muon's anomalous magnetic moment to about 7 parts per million, Hughes and collaborators at Yale and Brookhaven thought that they could eventually do 20 times better at Brookhaven's Alternating Gradient Synchrotron (AGS).

At the heart of their undertaking was a proposal to build a 14-meter-diameter muon storage ring with an iron-core superconducting magnet producing a 1.5-tesla bending field of unprecedented stability and homogeneity throughout the ring's 9-cm beam aperture. By the end of the decade, the collaboration having become quite international, construction began. The ring, shown in figure 1, was designed by Gordon Danby (Brookhaven). Sporting the world's

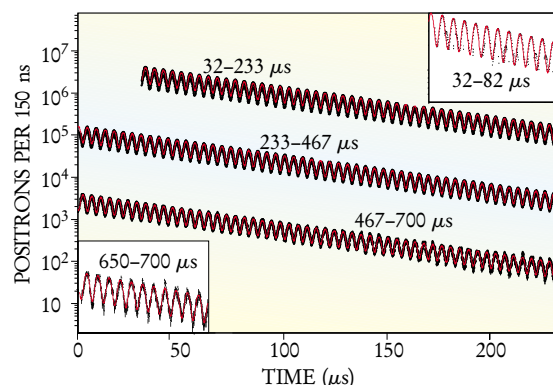


FIGURE 3. POSITRON SIGNAL decaying and oscillating for 700 μs after muon beam injection. The figure shows the complete 1999 data sample (black points) from all 24 detectors and the best 10-parameter fit (red curve). (The inserts are blowups.) The 4.4- μs oscillation is due to the small “anomalous” difference ω_a between the muon's precession and cyclotron frequencies. The fit yields ω_a to 1.3 parts per million. (Adapted from ref. 1.)

largest superconducting magnet, it began producing data in 1997.

The muons that circulate in the ring are the decay products of pions produced by 24-GeV protons from the AGS hitting a nickel target. The AGS's proton flux is more than 10 times that of the old CERN PS. The muon beam intensity of the Brookhaven experiment gains another factor of 10 over its CERN predecessor by having the muons formed into a monochromatic beam before injection into the ring. In the CERN experiment, pions were injected into the ring and then decayed.

Until this year, all data were taken with positive muons (μ^+). The muon beam circulates with a momentum of 3.09 GeV/c, chosen because it is the precise momentum at which relativistic effects happen to cancel any dependence of the frequency difference ω_a on the electrostatic quadrupole field required for vertical beam focusing. At this energy, relativistic time dilation extends the muon's 2.2- μs mean life to 64 μs , time enough for about 400 trips around the ring, on average, before it decays.

At injection, the μ^+ beam is 97% longitudinally polarized as a result of the parity-violating pion decay. The μ^+ decays to a positron and two neutrinos. The emission directions of the most energetic positrons (> 2 GeV) serve as a good monitor of the muon's spin direction at the moment of decay. Two dozen detectors are arrayed around the outside of the storage ring

to record energetic decay positrons coming out tangent to the circular beam orbit.

Because of its anomalous magnetic moment, the spinning muon precesses about the vertical 1.45-T bending field slightly faster than it circles the storage ring. The result is that the precessing spin (and the decay-positron distribution) gradually rotates away from alignment with the muon's momentum. It takes about 29 round trips, or 4.4 μs , for the precession to lap the muon's cyclotron orbit. This produces a 4.4- μs modulation in the decay-positron signal recorded by each of the detectors. (See figure 3.) With all 24 detectors recording the oscillating and decaying positron signals for 160 orbits after each muon-beam injection, the experimenters seek, over the course of the experiment, to measure the precise modulation frequency ω_a , and hence the muon's anomalous magnetic moment, to better than 0.4 parts per million.

Such precise determination of a_μ requires extremely careful surveillance of any spatial or temporal variations of the magnetic field B . To that end, the experiment employs several hundred fixed NMR field probes plus a traveling array of 17 NMR probes mounted on a trolley that sweeps through the storage ring's vacuum chamber twice a week. Feedback from the fixed probes to the magnet power supply keeps the field steady to 0.1 parts per million.

In recent months, the experiment has been running with negative muons. That's a good way of testing particle-antiparticle symmetry (the *CPT* theorem), and it can disclose unsuspected systematic experimental errors. Unfortunately, one gets fewer μ^- per AGS proton. Furthermore, to prevent electron sparking, μ^- beams require very high vacuum. So the going is slower. “To reach the original goal of measuring a_μ to 0.35 part per million,” says Roberts, “we'd probably have to run again in 2002. But there's a chance that the winding down of particle physics at the AGS might relegate our unique facility to mothballs before that.” **BERTRAM SCHWARZSCHILD**

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