spinning with a leisurely period of about 10 seconds. To have enough rotational energy to power ASASSN-15lh, a magnetar would have to spin with a millisecond period. Astronomers have never seen a millisecond magnetar, possibly because any magnetar born with such a short period would lose the bulk of its rotational energy in just a few months. Moreover, theorists recognize, a millisecond magnetar is spinning so rapidly that it is on the verge of centrifugally blowing itself apart. The magnetar model seems capable of explaining ASASSN-15lh, but just barely. If the object is a magnetar-powered SLSN, it may be almost literally the most energetic supernova conceivable.

Further oddities

Beginning in September, observations of ASASSN-15lh have revealed an unexpected increase in its power output and temperature. Much of the new power is in the UV. Magnetar theorist Brian Metzger notes that the neutral ejecta of a supernova are opaque to UV radiation, but in time they could be ionized, which would allow the UV to escape. It's too early to tell if the new bump in intensity has anything to do with that theoretical ionization breakout.

Most of the two dozen known SLSNe have been spotted in dwarf galaxies low in metals—that is, elements other than hydrogen or helium. But ASASSN-15lh was seen against a large metal-rich galaxy. As ASASSN-15lh fades and its host environment comes into better view, we might learn that the object was actually born in a currently invisible dwarf galaxy. But for now, the host of ASASSN-15lh represents a mystery.

For his part, Stanek relishes his role in contributing to a scientific puzzle. "I'm an observer, not a theorist," he says. "I'm very happy we found something super unusual, but whatever the data tell us, we will listen."

Steven K. Blau

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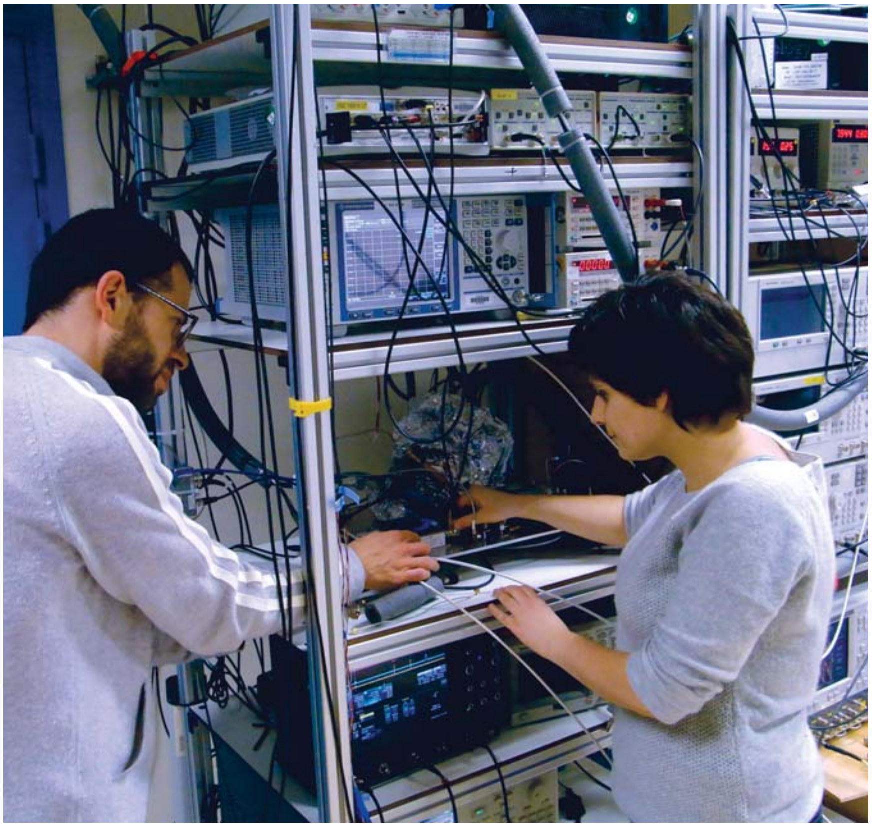
A resonant circuit accelerates spontaneous spin-flip transitions

Reducing the radiative transition's time constant from thousands of years to a fraction of a second could benefit quantum information schemes.

When an atom, molecule, or other quantum system is prepared in an excited state, it doesn't stay there forever. Sooner or later, with no apparent provocation, it decays into a lower-energy state and releases its excess energy, usually in the form of a photon. Although such spontaneous emission may seem like an inherent feature of the material system, it depends just as much on the vacuum into which the photon is emitted. That dependence is quantified by Fermi's golden rule: The probability of a transition is proportional to the density of final states—including the available photon states of the right energy.

Experiments by Serge Haroche and others in the 1980s showed that one can tinker with the rate of spontaneous emission by placing the emitting system in an optical cavity with a high quality factor. For a transition with energy near a cavity resonance, the density of available photon states—and thus the spontaneous emission rate—is enhanced. For transitions far from any resonance, spontaneous emission is suppressed.

Those experiments, the beginnings of the field of cavity quantum electrodynamics, focused on transitions between electronic energy levels in atoms. (See PHYSICS TODAY, December 2012, page 16, and the article by Serge Haroche and Daniel Kleppner, PHYSICS TODAY, January 1989, page 24.) Now, a team of researchers led by Patrice Bertet and Audrey



PATRICE BERTET

FIGURE 1. PATRICE BERTET (LEFT) AND AUDREY BIENFAIT (RIGHT) tune the microwave setup they used to excite electron spins and detect their spontaneous emission.

Bienfait (shown in figure 1) from the Atomic Energy Commission in Saclay, France, in collaboration with the groups of John Morton at University College London and Thomas Schenkel at Lawrence Berkeley National Laboratory, have demonstrated the same effect in a different system: the electron spins in a solid.[1] Using a superconducting resonant circuit, they've increased the spin-flip transition's spontaneous emission rate by a factor of nearly a trillion.

Cavities and circuits

The new work comes close to realizing the first theoretical description of cavity-enhanced spontaneous emission. In a 1946 conference abstract, NMR pioneer Edward Purcell laid out a proposal for accelerating the relaxation of nuclear spins.[2] When the spins are placed in a cavity, he said, the rate of spontaneous emission would be boosted by a factor proportional to the cavity's quality factor and inversely proportional to its volume.

It was an ambitious suggestion. Even under the strong magnetic field of a modern conventional NMR system, the energy difference between nuclear spin states is tiny—around a millionth of an eV or less—and the density of photon states in free space is proportional to the photon's energy squared. That density of states, combined with the weakness of the nuclear magnetic moment, yields a spontaneous-emission lifetime longer than the age of the universe. Unsurprisingly, then, spontaneous emission is overwhelmed by nonradiative mechanisms for relaxation, such as coupling to phonons. To turn it into the dominant relaxation process would require a cavity of extraordinarily high quality factor and minuscule volume.

A hint of what was possible came in 1985, when John Clarke and colleagues observed evidence of spontaneous emission in chlorine nuclear spins.[3] They placed their sample, a sodium chlorate ($NaClO_3$) powder, not in a closed cavity but inside the coiled inductor of an *LC* circuit. Like a cavity, the circuit alters the allowed electromagnetic modes in the surrounding space: It enhances the density of states near resonances and depletes it elsewhere. From a small bump in the measured noise spectrum, the researchers concluded that they'd reduced the spontaneous-emission lifetime from trillions of years to about 100 million. But because their sample contained some 10^{21} spins, enough of them emitted

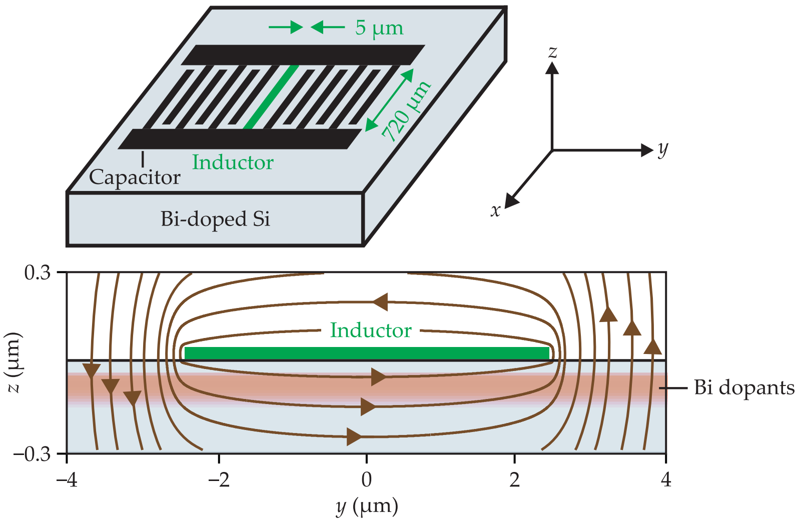


FIGURE 2. A MICRON-SCALE ALUMINUM *LC* CIRCUIT, composed of a straight-wire inductor (green) and comb-shaped capacitors, is fabricated on the surface of a bismuth-doped silicon sample. When the circuit is excited at its resonant frequency of 7.3 GHz, the oscillating magnetic field (brown) around the inductor interacts with the nearby Bi–electron spin pairs. The circuit's presence alters the spectrum of allowed photon states the spins can couple to and thus the spins' rate of spontaneous emission. (Adapted from ref. 1.)

photons over the course of the experiment to produce a visible signal.

Electrons have magnetic moments some three orders of magnitude larger than nuclei. So when subjected to a magnetic field in an electron spin resonance (ESR) experiment (the electron's equivalent of NMR), they acquire a splitting of tens of μeV, which equates to a frequency of several gigahertz. All told, their spontaneous-emission lifetime in free space is a relatively brief 10 000 years.

Seeking single spins

Bertet and company didn't set out specifically to enhance spin relaxation, although they always knew it was a possibility. Rather, their primary aim was to design an ESR experiment with single-spin sensitivity. They planned to create a nanometer-scale high-quality *LC* circuit, small enough to couple to a single electron spin. A circuit's dimensions function in a similar way to the cavity volume in Purcell's proposal: The smaller the circuit, the more strongly spins couple to it. And stronger coupling results in both greater sensitivity to tiny signals and greater potential enhancement of spontaneous emission.

As a first step toward the nanoscale, the researchers designed an *LC* circuit with micron dimensions,[4] as shown in figure 2. The capacitors took the form of intermeshed combs, and the inductor was not a coil but a straight wire. When a microwave pulse excites the circuit at its resonant frequency, an oscillating magnetic field encircles the inductor and couples to spins in the immediate vicinity.

The circuit was made out of aluminum, a low-temperature superconductor that Bertet's group has considerable experience in working with. But Al has a relatively low critical field of 15 mT; when placed in a magnetic field stronger than that, its superconductivity—crucial for achieving a sufficiently high quality factor—is destroyed. To compensate, the researchers needed to use a spin system with a large energy splitting even at low magnetic field.

Bismuth-doped silicon-28 has the necessary unusual property. At low temperature, each spin-9⁄2 Bi nucleus pairs with a spin-½ electron; the interaction between the two particles creates two available states—one with total spin 4 and one with total spin 5—that differ in energy by 7.4 GHz even with no applied magnetic field. Applying a field of a few millitesla lifts the degeneracy of the Bi nuclear spin to create a manifold of allowed transitions between 7.2 GHz and 7.6 GHz; adjusting the applied field

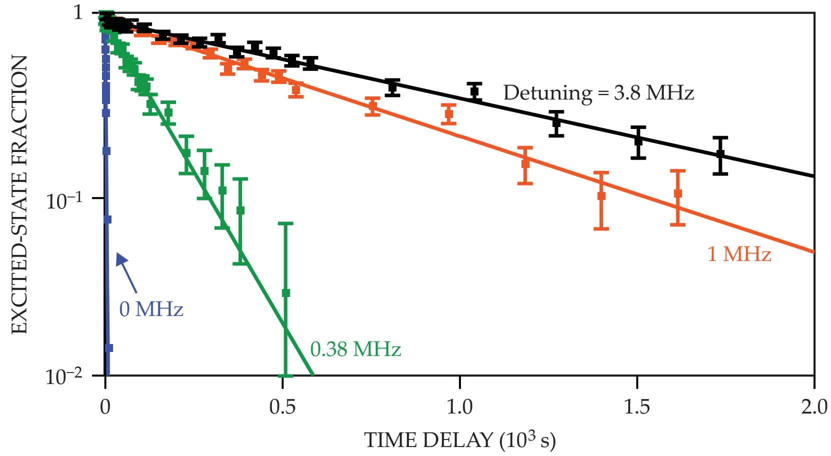


FIGURE 3. TUNING THE ENERGY of the spin-flip transition to exactly match the circuit's resonant frequency causes excited-state spins to relax rapidly, as shown by the blue data. When the transition energy is tuned slightly off resonance, the excited-state lifetime increases, as shown by the data in green, orange, and black. (Adapted from ref. 1.)

tunes the spin transition energies into and out of resonance with the *LC* circuit.

Incidentally, nitrogen–vacancy centers in diamond have the same property, with zero-field splitting around 3 GHz. "We could also have done the experiment with NV centers," says Bertet, "and if we used a metal with a higher critical field for the circuit, it would be straightforward to extend to any other electron-spin system."

The Si sample was doped with a low level of Bi so the paired spins would be separated widely enough to behave independently; some 10^4 spins were close enough to the inductor to couple to it. Using a pair of antennas to send and receive microwave pulses at the circuit's resonant frequency, the researchers excited the spins and subsequently measured their state. From the strength of their signal, they determined that the spin–circuit coupling should be strong enough to make spontaneous emission the dominant mechanism for spin relaxation.

To prove it, they measured the emission rate directly: To a sample cooled to 20 mK, they applied a microwave pulse to excite all the spins, waited an adjustable time *T*, then measured the fraction that remained in the excited state. In the absence of enhanced spontaneous emission, the excited-state population decays exponentially, via nonradiative mechanisms, with a lifetime of about half an hour. But when the spin-flip transition energy was tuned into resonance with the circuit, the excited-state lifetime dropped to just 0.35 s.

Nor was the enhancement all or nothing. By slightly detuning the transition from the circuit resonance, Bertet and company achieved a range of intermediate excited-state lifetimes, as shown in figure 3.

Reset button

Although specific applications may be a long way off, enhanced spontaneous emission from electron spins may find use in numerous areas. Of most interest to Bertet and colleagues is the ability to make ESR experiments faster and easier. In the current state of the art, once some spins are excited, there's no easy way to return the system to thermal equilibrium to begin again. Circuit-enhanced spontaneous emission could function as a kind of reset button that can be activated on demand.

PHYSICS UPDATE

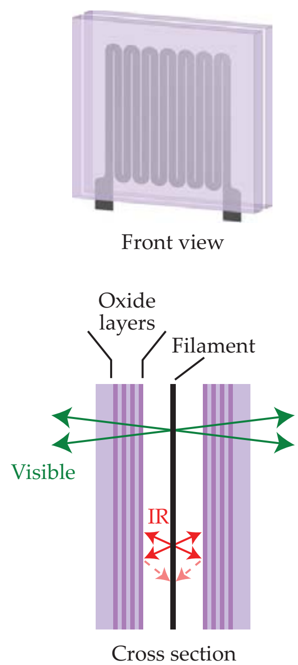
These items, with supplementary material, first appeared at www.physicstoday.org.

BORON NITRIDE NANOTUBES REINFORNCE POLYMER MATERIALS

One form of boron nitride is a white, lubricious, flaky material whose material properties resemble graphite's. By contrast, its nanotube form, like carbon's, is strong, tough, and light. Exploiting those desirable properties in a bulk material entails embedding the nanotubes in a lightweight matrix—provided the nanotubes bind strongly enough to the matrix material that they don't slip. Quantifying that binding was the goal of an investigation led by Changhong Ke of Binghamton University and Xianqiao Wang of the University of Georgia. The researchers created thin polymer films—of epoxy and of PMMA—and embedded them with boron nitride nanotubes (BNNTs). Cleaving the films left some BNNTs poking out from the surface. By welding a nanotube's protruding tip to an atomic force microscope, the team could determine how much force was needed to pull it out. For tubes buried deeper than about 200 nm, the force turned out to be 250 nN for the BNNT–epoxy composite and 190 nN for BNNT–PMMA. Less force was needed to extract carbon nanotubes (CNTs) from the same materials. Molecular dynamics simulations revealed the source of the BNNTs' stronger binding. Because BNNTs are made of two different elements—as opposed to one in the case of CNTs—their bonds are polar. And thanks to that polarity, BNNTs bind to the polymer matrix not just with van der Waals interactions but with Coulomb interactions too. Ke and Wang's findings suggest that BNNTs are excellent fillers for lightweight, high-strength composites. (X. Chen et al., *Appl. Phys. Lett.* **107**, 253105, 2015.) —CD

RECYCLING LIGHT

Conventional incandescent lightbulbs reach the 3000 K needed to emit in the visible range thanks to ohmic heating of a resistive tungsten filament. That process is extremely inefficient at producing light, though, because most of the spectrum of a 3000 K blackbody lies in the IR. Tailoring the spectrum by suppressing all but the wavelengths of interest can avoid the wasted energy. To that end, MIT researcher Ognjen Ilic, his postdoctoral adviser Marin Soljačić, and their colleagues surrounded the filament with interference filters that transmit visible light but reflect the IR. The idea of recycling unwanted IR emission to provide an additional source of heat to the filament isn't new. Two features distinguish the team's implementation: First, unlike earlier filters, which were designed for a single incidence angle, the MIT filters are made of thin layers of common oxides—ranging from the low-refractive-index silica to the high-index titania—that are effective over a wide range of wavelengths and angles. Second, the filament is planar, so it efficiently reabsorbs and reemits the reflected radiation; that shape also makes the filament interchangeable with advanced thermal emitters such as photonic crystals. The team's prototype, shown here, achieved a luminous efficacy—essentially the ratio of visible-light flux to consumed power—of 45 lum/W, roughly triple that of a conventional tungsten filament and approaching some commercially available compact fluorescent bulbs and LEDs. Numerical simulations predict that an optimized stack of 300 layers of four oxides can reach efficacies as high as 270 lum/W, far surpassing that of the best commercial lights. (O. Ilic et al., *Nat. Nanotechnol.*, in press, doi:10.1038/nnano.2015.309.) —RMW



NEUTRINO MAGNETOHYDRODYNAMICS

Neutrinos interact only weakly with ordinary matter. Yet in certain astrophysical contexts, such as supernova explosions, the coupled interactions between neutrinos and dense, highly ionized plasmas contribute significantly to a system's evolution. Modeling such systems is complicated enough even in the absence of neutrinos, and it normally requires analytic approximations or detailed numerical simulations. Adding neutrino effects entails further compromises; past approaches, for example, typically consider energy exchange between neutrinos and a neutral fluid. Now Fernando Haas and Kellen Alves Pascoal (Federal University of Rio Grande do Sul, Brazil) and Tito Mendonça (University of Lisbon, Portugal) propose a new framework for integrating relevant aspects of neutrino and plasma physics. Their approach, which they

A similar benefit could accrue to the field of quantum information. Normally, it's desirable for qubits to retain their state for as long as possible, but sometimes it's necessary to wipe the slate clean and start again.

Finally, the results may be applicable to the NMR technique of dynamic nuclear polarization. Because an atom's nuclear spin states are so close in energy, even under a strong applied magnetic field, it can be difficult to coax more of them into one state than the other. In a typical MRI, for example, nuclear polarization is measured in parts per million. Electron spins are easier to polarize because of their stronger magnetic moments, and under some circumstances it's possible to transfer electron polarization into nuclear polarization via a so-called flip-flop transition. The Bi–electron spin pairs undergo just such a transition—due to selection rules, flipping the electron spin necessarily changes the direction of the coupled Bi nuclear spin. It's possible that other flip-flop transitions could also be accelerated on demand.

Bertet and colleagues' next step is to follow their original plan and work toward a nanoscale resonant circuit. The smaller dimensions promise not only single-spin ESR sensitivity but even faster spontaneous emission.

Johanna Miller

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USING CARS TO GAUGE TORNADO STRENGTH

NOAA

In the 1996 blockbuster *Twister*, a semi-articulated fuel truck is lofted and flung by a writhing tornado into the path of the movie's storm-chasing heroes. Doubtless the filmmakers conceived the scene to demonstrate the fake tornado's terrible strength, but as a new study concludes, the movement of vehicles can actually be used to evaluate the strength of real tornadoes. Marius Paulikas and Thomas Schmidlin of Kent State University and Timothy Marshall of Haag Engineering examined field surveys of 959 passenger vehicles struck by tornadoes in 1994–2008. After classifying the vehicles according to whether they had been unmoved, displaced, rolled, or lofted, the researchers correlated the movements with the tornadoes' strength as determined by the damage inflicted on houses, trees, and other structures. For category EF3 and EF4 tornadoes, whose 136–200 mph winds can knock over trains and destroy entire stories of houses, 63% of cars were displaced, with 15% rolled or lofted. But for EF1 and EF2 tornadoes, whose 86–135 mph winds can upturn mobile homes and uproot trees, 65% of cars were not moved at all. Currently, wind's impact on cars is not taken into account when assigning an EF category to a tornado. Paulikas, Schmidlin, and Marshall's study suggests that including cars could improve the scale's accuracy, especially in the absence of buildings and trees. It also suggests that cars could be safer havens than mobile homes. (M. J. Paulikas, T. W. Schmidlin, T. P. Marshall, *Weather Climate Soc.* **8**, 85, 2016.) —CD

dub neutrino magnetohydrodynamics (NMHD), systematically extends MHD, which treats a plasma's electrons and ions as fluids and considers the dynamics of the magnetic field they produce, to include the weak interaction, which in particle physics describes the coupling between neutrinos and electrons. Adopting standard simplifying assumptions from MHD theory, the researchers obtain a set of 11 coupled partial differential equations that they show should hold over a range of astrophysical conditions. In particular, they find that neutrinos can prevent magnetic field lines from freezing, even in an ideal plasma. They also derive a new, neutrino-driven plasma instability that should play a central role in a supernova's strongly magnetized environment. (F. Haas, K. A. Pascoal, J. T. Mendonça, *Phys. Plasmas* **23**, 012104, 2016.) —RJF

COMBING FOR A SIGNAL BURIED IN NOISE

Picking out a signal from a sea of noise is a ubiquitous research challenge. If the signal recurs, multiple measurements can be appropriately averaged to improve the signal-to-noise ratio. For a single transient event, Fourier decomposition—breaking the signal down into its frequency components—can help isolate signal from noise. The signal's frequency components are correlated in phase with each other, whereas those of the noise are not. When the components are summed as complex numbers that encode phase and amplitude, only the signal adds up coherently. Calculating the Fourier transform works well enough for slow signals lasting a few microseconds, but faster signals run up against the resolution limits of both detectors and analog-to-digital converters. Now a University of California, San Diego, group led by Stojan Radic has employed tunable optical frequency combs, developed in Radic's lab, to catch those faster signals. (For more on frequency combs, see PHYSICS TODAY, June 2000, page 19.) The researchers used two phase-locked combs with slightly different spacing between their teeth. They combined a test signal—an 80-ps microwave pulse laden with white noise—with the first comb to make copies of the signal at each tooth. Using the second comb's teeth as reference frequencies, the researchers measured a narrow slice of each copy and thus partitioned the data into frequency bins. The outputs of those bins could then be summed. The gain in signal-to-noise ratio is limited only by the number of copies one can generate. The researchers have tested up to 300 copies for a gain of 25 dB. The group's tunable frequency combs are already commercially available, and Radic is eager to see how other researchers put his setup to use. (V. Ataie et al., *Science* **350**, 1343, 2015.) —SC PT