forward. The next steps will be to see if this holds true for other supernova remnants and to determine the actual composition and size distribution of this dust. However, the effect of supernova dust on the interstellar medium in galaxies depends on whether it can survive the shocks that will bring it to rest. Determining the fate of supernova dust—for example, by studying the x-ray emission from the elements released by the grains destroyed in the shocked ejecta—is a challenge for the future.

References and Notes

1. M. Matsuura *et al.*, *Science* **333**, 1258 (2011).
2. B. T. Draine, *Physics of the Interstellar and Intergalactic Medium* (Princeton Univ. Press, Princeton, 2011).
3. B. T. Draine, in *Cosmic Dust: Near and Far*, T. Henning, E. Gruen, J. Steinacker, Eds., ASP Conference Series Vol. 414 (Astronomical Society of the Pacific, San Francisco, 2009), pp. 453–472.
4. B. Sibthorpe *et al.*, *Astrophys. J.* **719**, 1553 (2010).
5. M. J. Barlow *et al.*, *Astron. Astrophys.* **518**, L138 (2010).
6. B. Ercolano, M. J. Barlow, B. E. K. Sugerman, *Mon. Not. R. Astron. Soc.* **375**, 753 (2007).
7. M. J. Barlow, J. Silk, *Astrophys. J.* **211**, L83 (1977).
8. B. T. Draine, E. E. Salpeter, *Astrophys. J.* **231**, 438 (1979).
9. E. Dwek, J. M. Scalo, *Astrophys. J.* **239**, 193 (1980).
10. C. F. McKee, *Interstellar Dust*, L. J. Allamandola, A. G. G. M. Tielens, Eds., ASP Conference Series Vol. 135 (International Astronomy Union, 1989), pp. 431–443.
11. A. P. Jones, A. G. G. M. Tielens, D. J. Hollenbach, C. F. McKee, *Astrophys. J.* **433**, 797 (1994).
12. E. Dwek, F. Galliano, A. P. Jones, *Astrophys. J.* **662**, 927 (2007).
13. R. Diehl *et al.*, *Nature* **439**, 45 (2006).
14. L. J. Tacconi *et al.*, *Nature* **463**, 781 (2010).
15. Image provided courtesy of R. Genzel based on observations reported in (***14***).

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PHYSICS

Switching Light by Vacuum

An opaque cloud of cold atoms becomes transparent when a few photons occupy an empty cavity, creating an optical switch for processing quantum information.

Michael Fleischhauer

When it comes to designing a quantum information network for applications such as computing or cryptography, photons have almost everything: They are fast, cheap, easy to guide and manipulate, and they can even be stored in quantum memories. However, building a switch or shutter that is sensitive to the quantum state of a single photon (in other words, that allows the creation of an all-optical quantum logic gate) is a long-standing and still unsolved problem. The experimental breakthrough reported on page 1266 of this issue by Tanji-Suzuki *et al.* (*1*) has brought us substantially closer to a solution. Their method changes the optical transparency of a cloud of cold atoms by using what might appear to be "nothing"—the electric field produced by a small empty cavity that can trap photons. The method causes the cloud to go from opaque to transparent (and back again) with just 10 photons.

The authors' technique is a variant of a phenomenon well known in quantum optics as electromagnetically induced transparency (EIT) (*2*). In EIT, a light field, called a control field, renders an ensemble of atoms in a gas or a solid transparent to a second light field, which otherwise would be absorbed. Associated with the EIT is a reduction of the group velocity (the change in apparent light speed caused by the refractive index of a material) that may be large enough to delay a light pulse in time by more than its pulse duration. Such delays are useful in creating optical circuits.

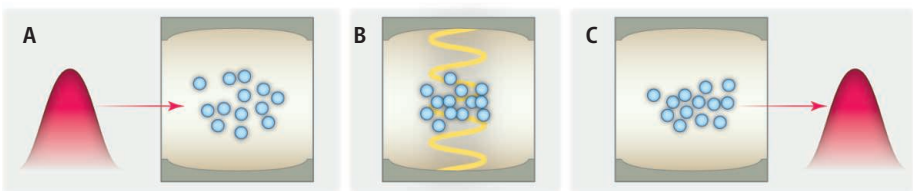
In the experiment of Tanji-Suzuki *et al.*, the role of the control field was taken over by the radiation mode of a microcavity. The microcavity was initially prepared in the vacuum state (no photons present) and loaded with an ensemble of cold atoms. The very small volume made the electric field per photon inside the microresonator very large. Furthermore, the resonator has a high quality factor (it resonates or "rings" for a long time), which means that it traps photons for a long time.

In cavity quantum electrodynamics, these conditions are known as a strong coupling regime, and they ensured that when the authors irradiated the atoms with a laser field, the scattered photons would be emitted into the resonator. Without the resonator, the scattered photons would be forever lost, and the laser field would be absorbed. However, the strong coupling created by a single photon in the resonator was sufficient to substantially modify the optical response of the cloud of atoms and avoid absorption.

Almost 20 years ago, Field predicted that if the coupling to the cavity mode is strong enough, even a vacuum field could induce transparency in a Raman medium (where three states are coupled optically) (*3*). This "vacuum-induced transparency" (VIT), as it was called by Field, has only now been demonstrated in the laboratory. The difficulty has been the intrinsic nonlinear character of VIT. In contrast with usual EIT schemes, which are driven by the absorption of many photons, in VIT there are only a few photons present in the atom cloud-cavity system at any time, and each one changes the system response substantially (hence, the need for a high-quality resonator).

In principle, a single photon is sufficient to achieve transparency, which is created by absorption of the photon from the probe field and subsequent stimulated emission into the resonant mode of the cavity (see the figure, panels A and B). After some time, the photon is eventually scattered back into the probe field in an inverse Raman process mediated by the collective response of all atoms in the ensemble (see the figure, panel C). In essence, the probe field has created its own transparency by coupling to the cavity and then re-emitting from this state. Tanji-Suzuki *et al.* have demonstrated this effect quite impressively with as few as 10 photons in the cavity.

Microcavities in the strong-coupling regime have long been promising candidates for key elements of quantum information processing with photons such as determin-



Vacuum-induced transparency. (**A**) A light pulse (red) enters an optical cavity and irradiates an absorbing cloud of cold atoms coupled to a microresonator initially in the vacuum state. (**B**) Strong coupling of the atoms to the resonator induces spontaneous Raman scattering of a single or a few photons into the resonator mode (shown as the gold wavy line). Although there are only a few photons in the resonator, they are sufficient to substantially modify optical response of the atom cloud to induce transparency. (**C**) After some time delay, the photons are scattered back from the resonator mode to the probe field, and the light pulse is re-emitted.

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istic single-photon sources (*4*–*7*), quantum memories (*8*), or quantum switches with photons (*9*). In the present approach, an ensemble rather than a single atom was used, which led to a substantial reduction of the characteristic time scales by a factor $N^{1/2}$ for an N-atom cloud. Even more important, and in contrast to previous proposals, the input and output of the probe field was not mediated by the high-quality cavity but rather by the atomic ensemble. This approach allowed for longer operational times without sacrificing operational speed and also reduced the effects of losses. Finally, this experimental achievement is also quite different from recent experiments that demonstrated EIT in strongly coupling cavities with individual atoms (*10*, *11*). In those experiments, the control field was rather strong (essentially a classical external laser and closer to an EIT experiment) and not the field of a single photon scattered from the probe field into the cavity that would be needed for quantum switching.

The work by Tanji-Suzuki *et al*. has shown that transparency of an opaque medium and a substantial time delay can be induced by a few photons. Their demonstration suggests that the switching of light by light on the single-quantum level—an all-optical quantum gate—may soon be in reach.

References and Notes

1. H. Tanji-Suzuki *et al*., *Science* **333**, 1266 (2011); 10.1126/science.1208066.
2. M. Fleischhauer, A. Imamoglu, J. P. Marangos, *Rev. Mod. Phys.* **77**, 633 (2005).
3. J. E. Field, *Phys. Rev. A* **47**, 5064 (1993).
4. A. Kuhn, M. Hennrich, G. Rempe, *Phys. Rev. Lett.* **89**, 067901 (2002).
5. J. McKeever *et al*., *Science* **303**, 1992 (2004).
6. M. Hijlkema *et al*., *Nat. Phys.* **3**, 253 (2007).
7. A. D. Boozer, A. Boca, R. Miller, T. E. Northup, H. J. Kimble, *Phys. Rev. Lett.* **98**, 193601 (2007).
8. H. P. Specht *et al*., *Nature* **473**, 190 (2011).
9. K. M. Birnbaum *et al*., *Nature* **436**, 87 (2005).
10. T. Kampschulte *et al*., *Phys. Rev. Lett.* **105**, 153603 (2010).
11. M. Mücke *et al*., *Nature* **465**, 755 (2010).

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MOLECULAR BIOLOGY

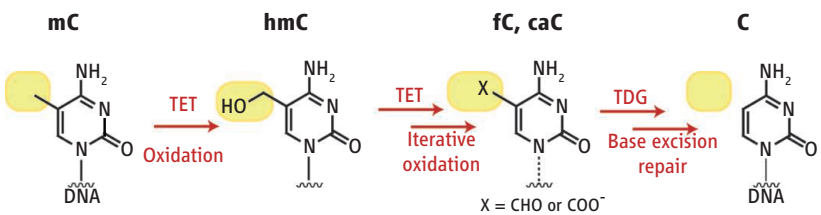
Demystifying DNA Demethylation

DNA modifying and repair enzymes make a new connection in the mechanism of DNA demethylation.

Christopher S. Nabel and Rahul M. Kohli

Variability and adaptability are necessary for overcoming the challenges of multicellular life. To address this need, nature has evolved a substantial enzymatic toolbox for altering cytosine within the genome. Methylation of the nucleotide cytosine (C) at the 5-position of the base has profound impacts on gene expression and cellular identity. The reverse of this process, DNA demethylation, is equally important for cleaning the genomic slate during embryogenesis or achieving rapid reactivation of previously silenced genes. Although the mechanism of DNA methylation has been rigorously established, active DNA demethylation in mammals has remained enigmatic, as disparate observations have failed to coalesce into a consistent model. Cytosine deamination, oxidation, and base excision repair enzymes have been proposed in a dizzying variety of combinations (*1*). Against this backdrop, two reports in this issue, by Ito *et al*. (*2*) on page 1300 and He *et al*. on page 1303 (*3*), help bring new clarity to the mechanistic model for DNA demethylation.

The studies by Ito *et al*. and He *et al*. expand on the recent discovery that 5-methylcytosine (mC) can be oxidized to 5-hydroxymethylcytosine (hmC) by TET enzymes, members of the α-ketoglutarate–dependent oxygenase family (*4*). Although hmC exists in low quantities—less than 1% of all cytosines (*5*)—the base has become a commodity in the epigenetics field, particularly given studies implicating TET in global and locus-specific DNA demethylation (*6*–*8*). One notable proposal posits that iterative oxidation by TET could yield 5-formylcytosine (fC) and 5-carboxylcytosine (caC) (*1*). Given the precedent of a decarboxylase in pyrimidine salvage, a similar enzyme could ultimately regenerate cytosine.



DNA demethylation. TET enzymes are proposed to oxidize 5-methylcytosine (mC) to 5-hydroxymethylcytosine (hmC) and subsequently to generate the higher oxidation substituents 5-formylcytosine (fC) and 5-carboxylcytosine (caC) (shown as the structure with the 5-X substituent). Unmodified cytosine (C) is on the far right. Base excision repair, initiated by thymine-DNA glycosylase (TDG), releases and replaces the entire modified oxidized base with unmodified C.

In evaluating this proposal, Ito *et al*. and He *et al*. both demonstrate that TET enzymes are capable of iterative oxidation of mC. Purified TETs converted hmC to fC and caC in oligonucleotides. In mouse embryonic stem (ES) cells, both fC and caC were detected in the genome by mass spectrometry, albeit at low amounts, confirming the recent detection of fC in ES cells (*9*). Accumulation of higher oxidation products depended on TET, as the absence of a TET isotype decreased amounts of the modified bases in ES cells. The discovery of these seventh and eighth bases, after the sixth base hmC, provides clear evidence that we have underestimated the dynamic nature of the genome (*10*).

How can higher oxidation products of mC revert to cytosine? Although Ito *et al*. suggest an unknown decarboxylase, He *et al*. propose direct removal of the entire caC nucleobase by thymine-DNA glycosylase (TDG). Subsequent repair of the resulting abasic site would restore unmodified cytosine. TDG has been previously implicated in demethylation, as its absence is embryonic lethal and perturbs DNA methylation patterns (*11*, *12*). A requirement for TDG has fostered the prevailing assumption that demethylation must involve deamination, as the canonical TDG substrates are mispairs between thymine and guanine nucleotides that result from deamination of genomic mC. However, TDG has some activity against cytosine analogs, particularly when substituents weaken the *N*-glycosidic bond between the nucleobase and the sugar (*13*), as would likely be the case for fC and caC. Indeed, He *et al*. show that ES cell lysates contain glycosylase activity against caC-containing oligonucleotides—activity that is lost when TDG is depleted. Furthermore, TDG overexpression decreases genomic

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