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Elizabeth A. Donley
Science **342**, 942 (2013);
DOI: 10.1126/science.1247392

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PHYSICS

A View on Energy Transfer Between Cold Atoms

Elizabeth A. Donley

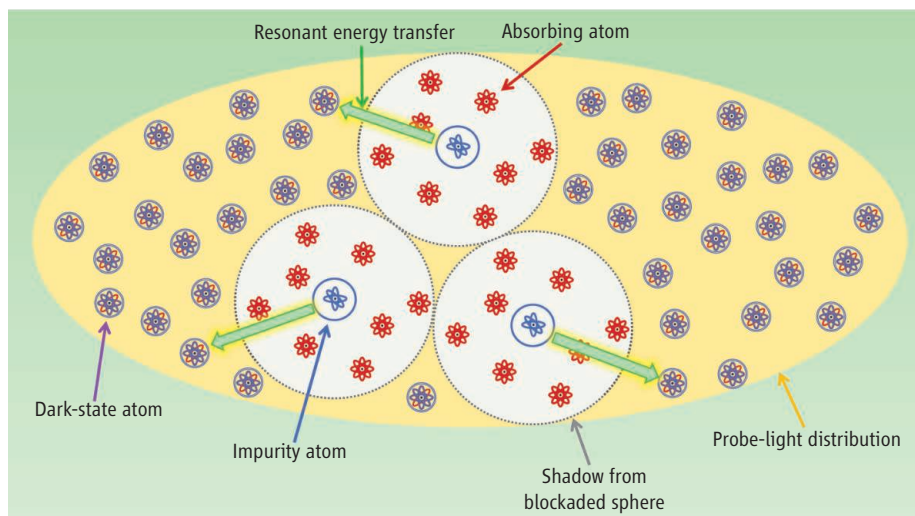
Atoms with highly excited electrons—called Rydberg atoms—have many exaggerated properties compared with ordinary ground-state atoms. For example, the loosely bound electrons create large dipoles that lead to long-range interactions between Rydberg atoms that are many orders of magnitude stronger than those between ground-state atoms. Strong interactions between Rydberg atoms can enable energy transport over distances many times the size of the atoms (1). On page 954 of this issue (2), Günter *et al.* describe how they have nondestructively and continuously imaged resonant-energy transfer between cold ^{87}Rb Rydberg atoms with controlled coupling to the environment. Their technique may enable the engineering of open quantum systems for quantum simulation (3), which could lend insight to the transition from classical to quantum energy transport in complex systems. The nature of this transition in a dissipative environment remains an open question and may have relevance to the efficiency of dipole-coupled energy transport in molecular systems such as photosynthetic light-harvesting complexes (4).

Another phenomenon resulting from strong long-range interactions of Rydberg atoms is known as the Rydberg blockade (5). The resonant photoexcitation of one Rydberg atom strongly suppresses the excitation of neighboring atoms because their interactions shift the energy levels of the neighbors out of resonance with the excitation light. This effect limits the density of Rydberg atoms that can be created in an atom cloud.

To directly view distributions of Rydberg atoms, Günter *et al.* developed an imaging technique based on electromagnetically induced transparency (EIT) resonances in blocked probe atoms that surround “impurity” Rydberg atoms. As an initial demonstration, they created the impurity atoms in the $|50S\rangle$ excited state—highly excited compared with the $|5S\rangle$ ground state for the valence electron of ^{87}Rb . After they created the Rydberg impurities, lasers operating at two different

Time and Frequency Division, National Institute of Standards and Technology, Boulder, CO 80305, USA. E-mail: edonley@boulder.nist.gov

A new method for visualizing energy transfer between highly excited atoms may provide insight into coherent energy transport in molecular systems.



Imaging energy transfer. Impurity Rydberg atoms (blue) were created by Günter *et al.* in the central region of a cloud of cold rubidium atoms. Their density is limited by the Rydberg blockade effect, and they are surrounded by a blocked sphere of probe atoms (red). Far from the impurities, the EIT lasers are resonant with the transitions in the probe atoms and the probe atoms go into a “dark state,” which is a quantum superposition of the ground and Rydberg states that transmits the light. Strong interstate Rydberg interactions shift the energy levels for probe atoms around the impurities such that the EIT resonance condition is not met and they absorb probe light, casting shadows on a camera. Hopping of the excitation energy from the impurity atoms to dark-state probe atoms (shown in green) is observed as the shadows diffuse outward. Here, the atom distribution is shown projected onto the camera intensity distribution.

frequencies (a strong coupling laser and a weaker probe) were tuned to an EIT resonance (6) between the ground state and a lower-energy Rydberg state in the remaining probe atoms. The probe atoms near a Rydberg impurity absorbed photons because their energy levels were shifted out of EIT resonance, whereas probe atoms far from a Rydberg atom remained in the transparent EIT “dark state.” Thus, each Rydberg impurity was surrounded by a sphere of absorbing probe atoms marking its position, and shadows appear on camera images around the Rydberg impurities. Many tens of probe atoms per impurity atom can absorb light and amplify the signal from an individual Rydberg atom.

Günter *et al.* used this imaging technique to demonstrate excitation transport between Rydberg impurities and probe atoms. The impurities were now in the $|38S\rangle$ state. The probe atoms were probed with EIT resonant with the $|37S\rangle$ state—close in energy and strongly coupled to the $|38S\rangle$ state through the $|37P\rangle$ state. They first created a sample of impurities in the central region of the cold-

atom cloud and then illuminated a broader portion of the sample with the EIT light. With continuous illumination, the shadow from the absorbing probe atoms near the impurities diffused outward with time and grew to fill the whole region that was illuminated by the EIT light.

A value for the preferred hopping distance for the excitation energy of about $6\ \mu\text{m}$ was determined. This length scale was set by a trade-off between the interstate Rydberg blockade (the density of dark-state probe atoms is appreciable only outside of the blocked sphere) and the scaling of the dipole-dipole exchange interaction. This energy-hopping distance is about 60 times as great as the radius of the Rydberg atom wave functions. To confirm that the excitation was caused by hopping to probe atoms in the dark state, they did a control experiment in which they initially left the EIT light off and probed the distribution of impurities for a brief period after a variable delay. They confirmed that without the EIT light, energy hopping did not take place and the width of

the distribution of impurities did not grow with time. Thus, the environment as controlled by the laser fields had a strong influence on the observed energy transport.

It is likely that in future uses of these techniques, quantum-simulation studies can be performed in open quantum systems with controlled energy hopping and decoherence rates. The ratio of these rates determines whether the energy transport occurs in the classical

or quantum regimes. If the energy hopping rate exceeds the measurement-induced decoherence rate, then quantum coherent energy transport occurs. It may be possible to control and lower the decoherence rate to allow for studies of coherent excitonic behavior, which may bring insights to theories on energy transport in complex molecular systems such as light-emitting organic systems and photosynthetic proteins.

References

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10.1126/science.1247392

BIOCHEMISTRY

Not an Oxidase, But a Peroxidase

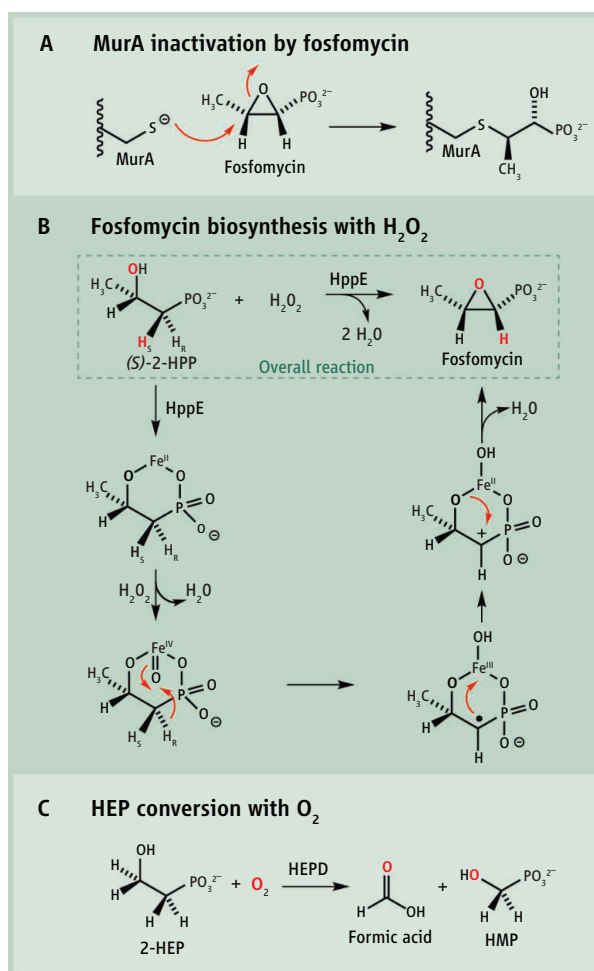
Frank M. Raushel

Fosfomycin (see the figure, panel A) is a deceptively simple antibiotic that is clinically effective for the treatment of gastrointestinal and lower urinary tract infections (1). The biological target of this compound is the bacterial enzyme MurA, which plays a key role in bacterial cell wall biosynthesis. On page 991 of this issue, Wang *et al.* (2) report that a key step in the biosynthesis of fosfomycin requires hydrogen peroxide (H_2O_2) rather than molecular oxygen (O_2). This discovery clarifies how the strained epoxide ring of fosfomycin is synthesized by bacteria and enhances understanding of the catalytic repertoire of iron-activated enzymes.

MurA catalyzes the transfer of the enolpyruvyl group from PEP to UDP-*N*-acetylglucosamine in an essential step of bacterial cell wall biosynthesis. Fosfomycin functions as a structural mimic of PEP. The highly strained epoxide ring of the antibiotic is attacked by a cysteine residue in the MurA active site to generate a covalent enzyme-fosfomycin adduct that renders the enzyme inactive (see the figure, panel A) (3). The pharmacological function of fosfomycin is thus dictated by the structural similarity to PEP and the inherent chemical reactivity of the strained epoxide ring.

In fosfomycin-producing organisms, the antibiotic is constructed in a five-step biosynthetic pathway (4). The epoxide group is assembled in the last step of this pathway from *S*-HPP. During the conversion of *S*-HPP to fosfomycin, catalyzed by the enzyme HppE, two electrons and two hydrogen atoms must be removed from the substrate. O_2 was long thought to be the

A key step in the biosynthesis of the antibiotic fosfomycin requires hydrogen peroxide, rather than molecular oxygen as previously assumed.



Oxidant action. (A) The antibiotic fosfomycin acts by inactivating the enzyme MurA, which plays a key role in bacterial cell wall biosynthesis. (B) It was long thought that fosfomycin biosynthesis, which is catalyzed by the HppE enzyme, requires molecular oxygen (O_2). Wang *et al.* propose an alternative mechanism in which H_2O_2 serves as the oxidant. (C) The HEPD enzyme is structurally similar to HppE yet requires O_2 as the oxidant.

is incorrect. The actual oxidant is H_2O_2 , and HppE is thus a peroxidase rather than an oxidase.

The three-dimensional x-ray structure of HppE shows that the active site is composed of a non-heme iron center (6). When the substrate, HPP, binds to the enzyme, it is coordinated to the iron center by the hydroxyl group and one of the oxygens from the phosphonate moiety (6). Isotopic labeling studies have revealed that one of the hydrogen atoms from the methylene group ($-CH_2-$) of the substrate is ultimately

ultimate recipient of the two electrons (5), but the reduction of O_2 to two water molecules requires four electrons. Therefore, two additional electrons from nicotinamide or flavin coenzymes were thought to be required for the activation of O_2 . Wang *et al.* now show that this view of the catalytic mechanism of epoxide formation by HppE

found in solvent water and that the epoxide oxygen of fosfomycin derives from the hydroxyl group of the substrate (7, 8).

In the originally proposed reaction mechanism, the iron center of the enzyme-substrate complex bound O_2 (4). This binding event initiated the reduction of O_2 via transfer of electrons from the ferrous

Department of Chemistry, Texas A&M University, College Station, TX 77843, USA. E-mail: raushel@chem.tamu.edu