Optically dressed magnetic atoms

The continuing decrease of the size of the structures used in semiconductor electronics and in magnetic information-storage devices has dramatically reduced the number of atoms necessary to process and store one bit of information: An individual magnetic atom would represent the ultimate size limit for storing and processing information. Towards this goal, we have demonstrated that an individual manganese atom embedded in a semiconductor quantum dot may act as a spin-based memory. Further, a pair of Mn atoms can act as a prototype of a pair of coupled memory units. We can exploit the optical absorption and emission of the quantum dot in order to initialize and to read out the spin state of the magnetic atoms. Under resonant optical excitation, we can enter the "strong coupling" regime where hybrid states of matter and the electromagnetic field are created, and this could be used for a coherent, optical "manipulation" of the Mn spin.

In our research, the quantum dot is an island of the semiconducting compound CdTe inside a layer of ZnTe. Absorption of an incident photon creates an electron-hole pair (an "exciton") in the quantum dot, see Fig. 1. Inversely, a photon is emitted when the two carriers annihilate each other.

With a single Mn atom introduced in the dot, the energy and polarization of the photon emitted or absorbed by the dot depends on the spin state of the S=5/2 magnetic atom. This is due to the exchange interaction present in the excited state, between the confined electron-hole pair and the Mn spin. The exciton acts as an effective magnetic field, directed along the dot's growth axis z. This effective field splits the 2S+1=6 spin states of the Mn atom (which are almost degenerate in the absence of the exciton), leading to a 6 line optical spectrum for the quantum dot (e.g. Fig.2, top left).

We had already shown that laser excitation resonant with one of these optical transitions can be used to initialize a localized Mn spin and to probe its dynamics optically: The Mn atom behaves like an optically addressable long-lived spin-based memory. To go further, information processing using individual spins will require fast coherent control of a single spin and also tuning of the coupling between two or more spins. We recently achieved two important steps towards these challenging goals.

Concerning the latter objective, for quantum dots containing two Mn atoms (which give complex spectra with up to 6x6=36 lines, e.g. Fig 2 at top right), we have shown that the precessional motions of the Mn spins become correlated with each other under optical excitation, as a result of their mutual interaction with the carrier spins. This carrier-mediated interaction could be exploited in the future to optically control the coupling between two Mn spins. Next, we have demonstrated that under a strong resonant optical field, the energy of any given spin state of one Mn atom or of a pair of Mn atoms can be tuned using the optical Stark effect. The intensity maps of Fig. 2 illustrate this for the case of the dot containing a pair of Mn.

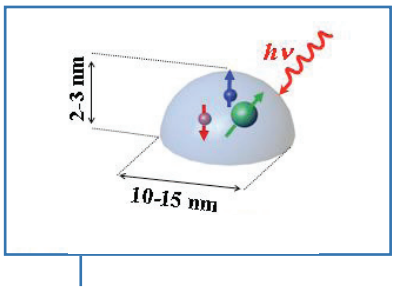

Figure 1: Illustration of a CdTe quantum dot containing an individual Mn atom (green) and an optically-created exciton (electron-hole pair).

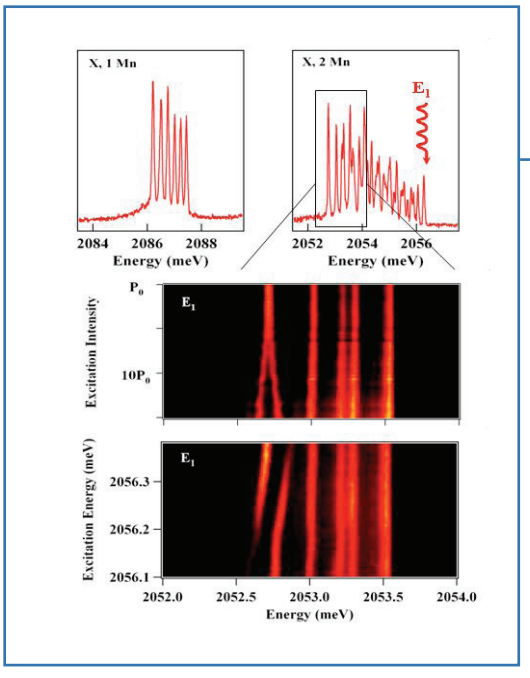

Figure 2: At top: Photoluminescence spectra (6 or 36 lines) resulting from the recombination of an exciton X in a CdTe quantum dot containing one Mn (left) or two Mn atoms (right). Below: Maps of photoluminescence intensity for the dot with two Mn atoms; a single mode laser excites the dot above the range shown. In the upper panel we vary the laser power (logarithmically) with the laser tuned to precise resonance with the highest energy excited state E_1 (spin state $|S_{z1}=S_{z2}=+5/2; J=+1>$) where S_{zi} and J are the angular momentum of Mn atom i and exciton respectively). In the lower panel, the laser is scanned through the energy E_1. One observes a power-dependent and tuning-dependent splitting of the recombination emission of the lowest energy excited state $|S_{z1}=S_{z2}=+5/2; J=-1>$. Since the ground state $|S_{z1}=S_{z2}=+5/2>$ is the same for both transitions, this shows that the Mn spins of the ground state are "dressed" by the resonant laser field.

Under optical excitation exactly resonant with an absorption transition, we can enter the strong coupling regime where hybrid states of matter and light are created. The ground state of the magnetic atoms is "dressed" with light. The spin dependent strong coupling with the laser field modifies the Mn fine structure (interaction with the crystal field) and hyperfine structure (interaction with the ^{55}Mn nuclei). The optically controlled energy shift affects the spin dynamics of the magnetic atoms. It will be used in future experiments for a coherent optical manipulation of both the electronic and the nuclear spins of individual and coupled Mn atoms.

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FURTHER READING

OPTICAL INITIALIZATION, READOUT AND DYNAMICS OF A Mn SPIN IN A QUANTUM DOT
C. Le Gall, R. S. Kolodka, C. L. Cao, H. Boukari, H. Mariette, J. Fernández-Rossier and L. Besombes
Phys. Rev. B 81, 245315 (2010).

OPTICAL STARK EFFECT AND DRESSED EXCITON STATES IN A Mn DOPED QUANTUM DOT
C. Le Gall, A. Brunetti, H. Boukari and L. Besombes
Phys. Rev. Lett. 107, 057401 (2011).