New Coordinated Projects

LOEWE priority project **SMolBits**

The state of Hesse funds a new collaborative priority project in the frame of the state initiative for the development of scientific and economic excellence (LOEWE) entitled "Scalable Molecular Quantum Bits (SMolBits)". The project, coordinated by Prof. Dr. Johann Peter Reithmaier, will start in January 2019 at the University of Kassel and will be funded for 4 years with about 4.4 Mio €. Seven CINSaT members (T. Baumert, M. Benyoucef, C. Koch, R. Pietschnig, J.P. Reithmaier, K. Singer, B. Witzigmann) from three disciplines (chemistry, physics and electrical engineering) are participating.

SMolBits

Further information

Website: http://www.uni-kassel.de/SMolBits

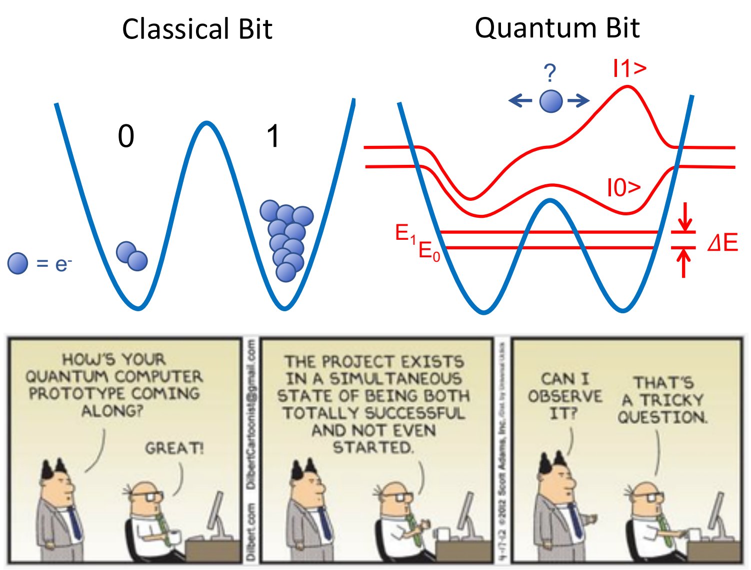

Fig. 1. Top left: Illustration of a classical bit defined by electrons charges localized in one of the potential wells. Only two values can be distinguished. A "1" is here defined by a certain minimum charge on the right hand potential. Top right: Illustration of a quantum bit. The electron can tunnel between the two wells and can be at any position in between. This situation can be described by probability wave functions |0> as symmetric overlap of the two single well wave functions or |1> as antisymmetric overlap, respectively. These so-called entangled states can be distinguished by the energy splitting ΔE. However, these are only the most extreme cases. Also any superposition state ψ = a |0> + b |1> is possible, which allow theoretically to store an infinite number of information in a single QuBit. Bottom: Cartoon addressing the consequence if one would transfer the strange behavior of entangled quantum states to a daily life situation.

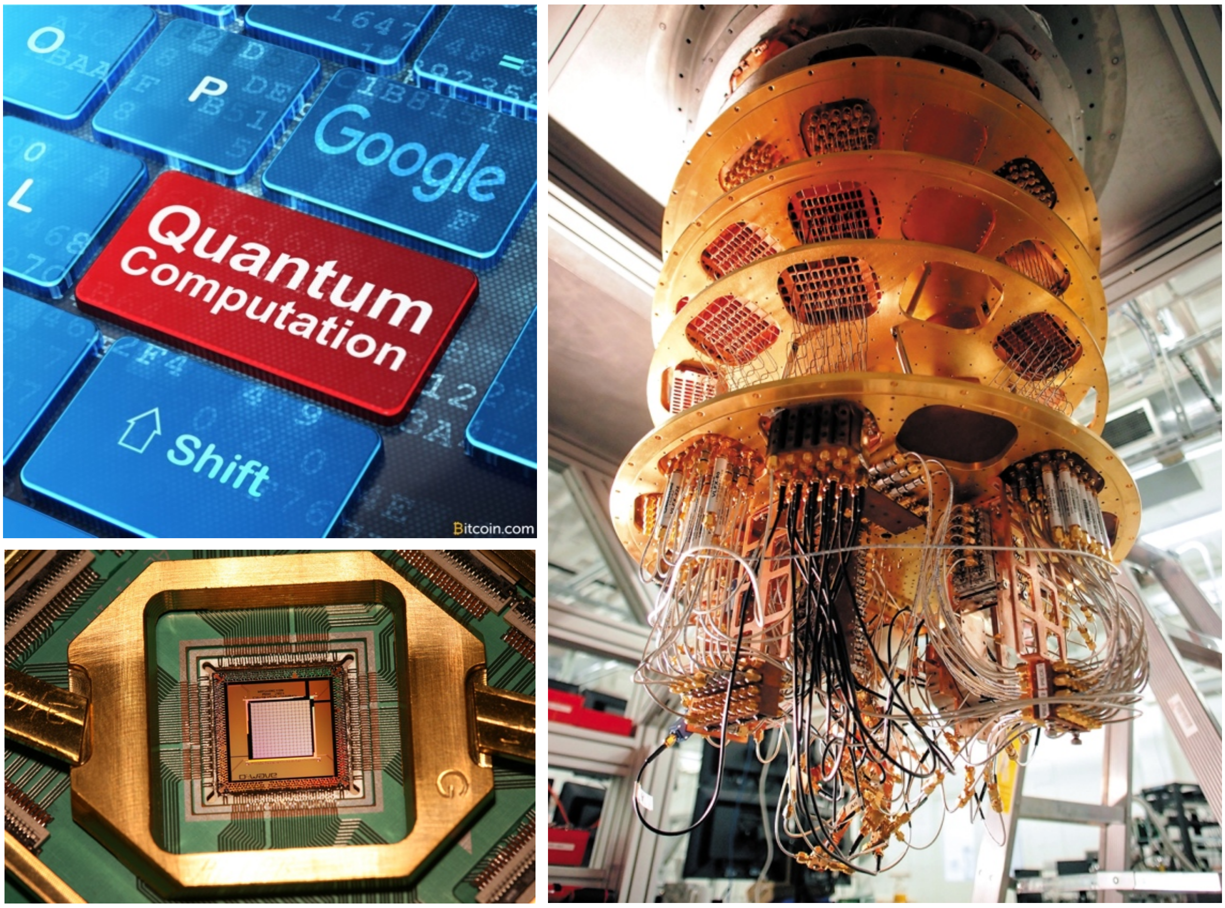

Fig. 2. On the left, an optical microscope picture of a superconductive quantum chip from google. On the right, the external wiring in a quantum computer set-up, which will be penetrated in a large cryostat cooled down below 1 K (less than -272 °C).

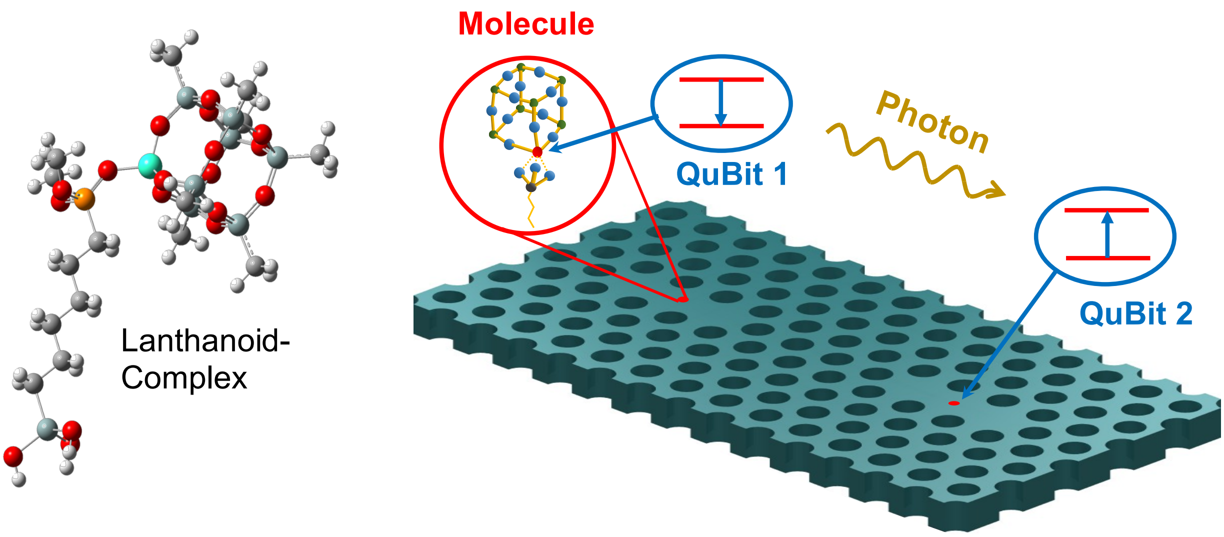

Fig. 3. On the left, schematic illustration of molecule complex consisting of a lanthanoid ion (bright blue ball) embedded in a rigid silicon based cage to suppress vibrational states and combined with a linker molecule for surface immobilization; On the right a simplified schematic picture of molecules (red dots) placed in the centers of optical nanocavities made of a nanostructured semiconductor membrane. Each single molecule acts as a quantum bit, which are optically coupled to each other by photons. For simplicity, the optical waveguides coupling the nanocavities are not shown.

Since the theoretical work of Albert Einstein describing the photo effect and Max Planck's work describing the black body radiation, people have realized that many physical effects, even those far away from atomic properties, cannot be explained without quantum mechanical considerations. Also many applications nowadays benefit from quantum mechanical phenomena such as the control of emission wavelength of light emitting diodes and lasers. These size effects deals mainly with the discretization of possible electron states in artificial nanostructures and are similar to the sharp dark lines seen in atom gas absorption spectra. In the meantime, more advanced aspects of quantum physics is explored resulting in a 2^{nd} generation of quantum mechanical applications. In this case, not only the discretization of energy states are considered but also non-classical correlations, such as entangled states. With this new generation of quantum mechanical instruments, one can think about using quantum mechanical principles for a new class of data storage and processing.

In figure 1, the main difference between a classical binary encoded memory and a quantum mechanically defined quantum bit is illustrated. In classical memory, e.g. the localized charge is used for the physical representation of the binary value "1". Here, one can only distinguish between two values, "0" or "1". In contrast, a quantum bit can represent many different states (in theory an infinite number). A single electron confined in a double quantum well, as illustrated in the top right part of figure 1, can be represented in quantum mechanics by a wave function with phase and amplitude while the square of the absolute value of the wave function corresponds to the probability to find an electron at a certain position. The red line wavefunctions represent here the extreme cases of the combination of two single well wavefunctions. While the |0> state consists of an in-phase (symmetric) overlap, the |1> state consists of an anti-phase (anti-symmetric) overlap. However, also a combination of these two states are possible forming a superposition or entangled state, which is called quantum bit (QuBit). A QuBit can theoretically represent an infinite number of combinations and is a key component for the predicted power of quantum computers beyond conventional computers.

Very recently, big companies, such as Google, Microsoft and IBM, have started spending significant amounts of money on developing first demonstrations of quantum computing exceeding limits of classical computing. In figure 2, the approach at Google is illustrated. Their approach, as of many other groups, is based on superconducting chips (see left bottom picture), which allow in the meantime the coupling of QuBits in the order of 100. The requests on control wiring and cooling down the whole system below 1 K is very demanding as can be seen in figure 2 (right panel). A scaling up of this approach to real practical complexities in the order of multiple thousands or millions of QuBits seems out of scope for the near future.

In the LOEWE priority project SMolBits a different and novel approach will be investigated, which addresses the scalability of quantum systems. Here, we want to utilize the nature's ability to reproduce identical quantum systems at the molecular level. In this project, we want to use lanthanoid complexes, as shown on the left of figure 3. The lanthanoid ion, marked in bright blue in figure 3, is embedded in a very rigid molecular cage to suppress vibrational excitations and is weakly linked to a linker molecule, which allows anchoring on functionalized solid surfaces. An optical transition of the core part of this lanthanoid complex works as a QuBit, which ideally can be identically reproduced. However, to address each of those QuBits, single molecules have to be localized on surfaces and connected to an optical network. In figure 3 (right), this is schematically illustrated based on a so-called photonic crystal nano-photonic platform. Here, the molecules are strongly coupled to optical nanocavities (i.e., areas with missing holes of the periodic structure), which are coupled themselves to each other by nano-photonic waveguides (not shown in the figure). The goal of the project after four years is to demonstrate for the first time the coherent optical coupling of two molecular QuBits on such a miniaturized nano-photonic chip and to understand the fundamental processes in such hybrid quantum systems.

To address these very challenging tasks, a unique interdisciplinary research consortium was built out of CINSaT members consisting of experts in chemical synthesis (Rudi Pietschnig), in ultra-short and coherent optical spectroscopy (Thomas Baumert), characterization of single molecules in ion traps (Kilian Singer), in semiconductor technologies and quantum optical characterization (Mohamed Benyoucef / Johann Peter Reithmaier), in computational photonics (Bernd Witzigmann) and quantum theory (Christiane Koch). To have these multiple expertise at one place is very unique in Germany as well as worldwide. Therefore, if the consortium will succeed in this 4-years project, it has a large potential to apply successfully for a collaborative research center (Sonderforschungsbereich) of the German Science Foundation and to establish "Quantum Technologies" as a long-term new focused research topic at the University.