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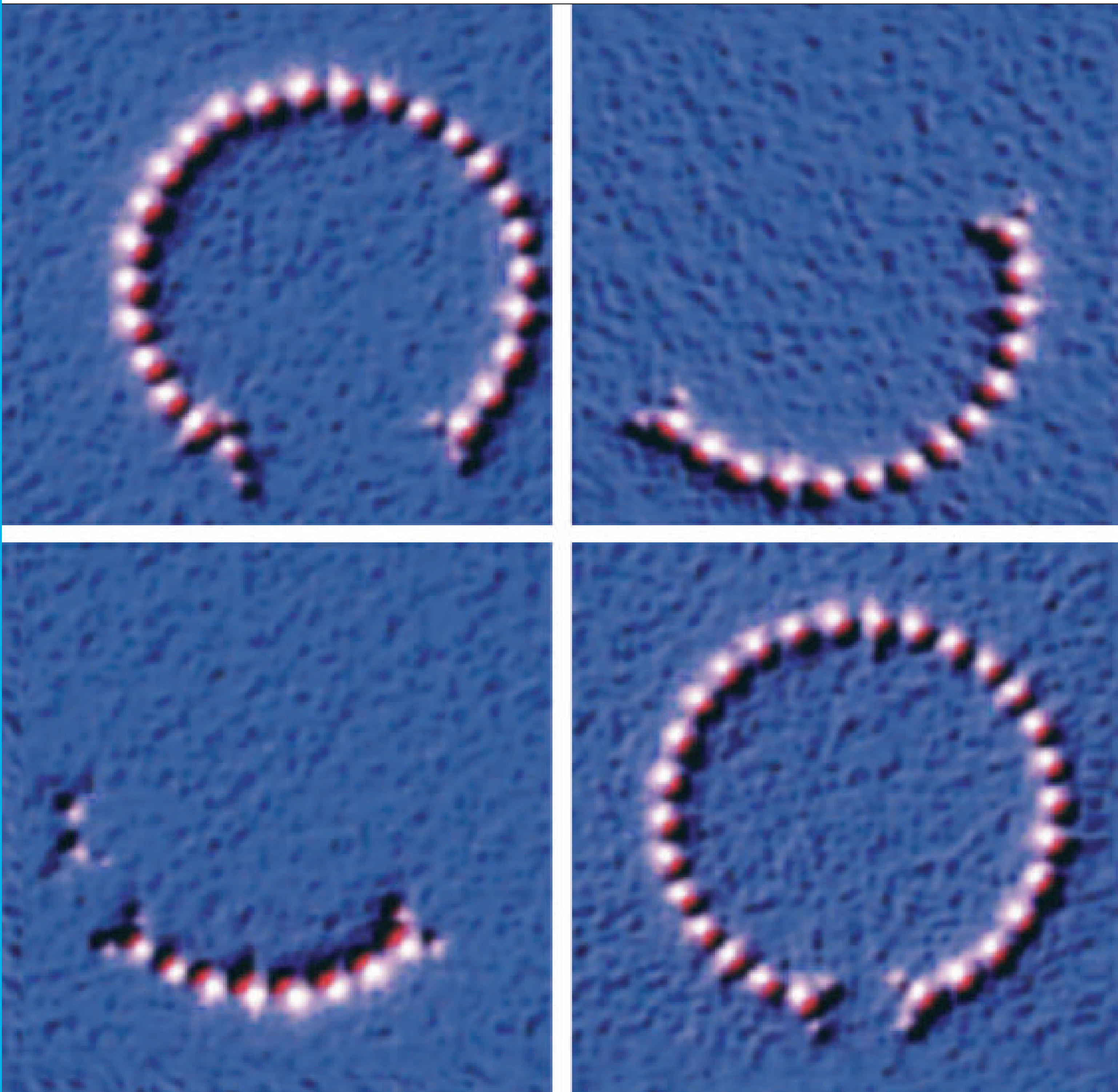
Arrays of Quantum Dots and Josephson Junctions (AQDJJ)

An ESF Standing Committee for Physical and Engineering Sciences (PESC) Programme



The physics and the properties of very small objects (for example, nanoparticles, Quantum Dots, Josephson Junctions) are among the main emerging issues of research in condensed matter physics. Arrays of these systems and their hybrid structures may not only display novel fundamental physics but also serve as a basis for future technologies. This network has been established to bring together leading theoretical and experimental researchers in Europe with the view to promote collaboration, further existing knowledge and to continue investigation of these novel areas of research.

The running period of the ESF scientific programme AQDJJ is for five years from June 2004 until June 2009.

Cover:
Discrete rotobreathers

Introduction

What are Quantum Dots?

The term Quantum Dot encompasses a wide variety of zero dimensional systems. If we consider that a line is a 1-dimensional object, then zero dimensional simply means a point or dot. Arrays of Quantum Dots are simply groups of these small objects joined together and considered as one system.

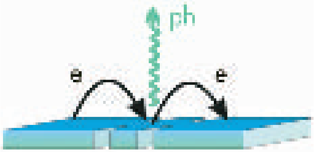


Figure 2 © E Weig, Germany

Figure 2 is a schematic drawing of a Quantum Dot, in which an electron tunnels from the source (on the left) to the island (in the middle), and then from the island to the drain (on the right), emitting a phonon in the process due to interaction with the lattice. Once on the island, the electron can be manipulated so that it behaves as a qubit (a quantum bit), and therefore this set-up could be used in quantum information processing.

Figure 3 © M S Garelli, UK

Figure 3 depicts two Buckyballs. A Buckyball is a C-60 fullerene molecule, containing an encased atom. The encased atom behaves as a qubit. Therefore this is an array of two quantum dots. Such arrays are easily scalable to any number of Buckyballs.

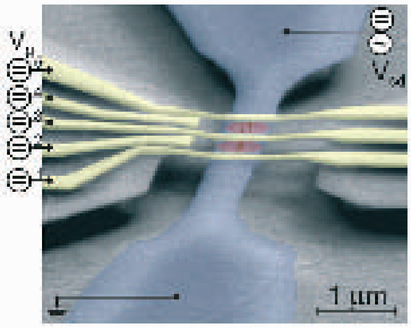


Figure 4 © E Weig, Germany

Figure 4 depicts a freely suspended, tuneable (via applying different gate voltages), two quantum dot system. A two-qubit system (together with single-qubit operations) is sufficient to implement arbitrary algorithms on a quantum computer.

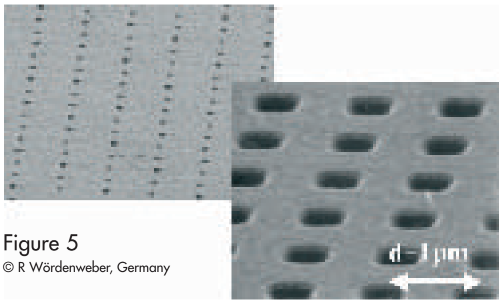


Figure 5
© R Wördenweber, Germany

A related concept is that of antidots (or holes), depicted in Figure 5. If there is a vacancy (hole) at each site, then electrons are free to move across this array of antidots. In this case, for example, we could consider the additional electron spin as the model for our qubit.

In systems consisting of arrays of small nanoscopic magnetic disks or quantum dots many new phenomena arise associated with magnetic pattern formation and fractal structures in particular. The fractal features may arise not only in the distribution of magnetic moments but also in their energy spectrum. The magnetization and the susceptibility of the system also display fractal characteristics. The signature of these fractal structures can be experimentally detected by various methods, in particular, by Kerr rotations. The system of nano-disks may be used to form memory cells and may form a three dimensional sandwich array, as presented in Figure 6 (following page).

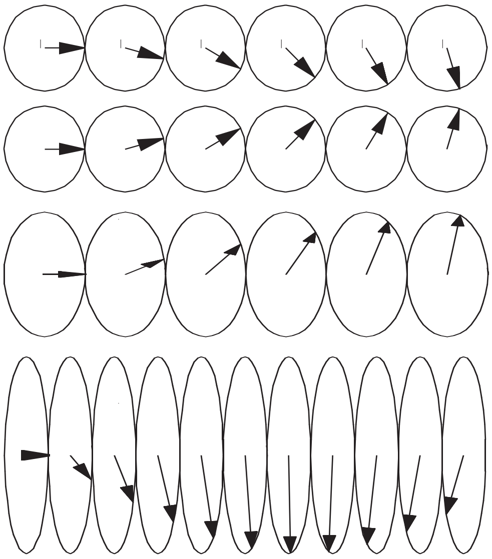


Figure 6 © K. Kürten, Austria & F V Kusmartsev, UK

Superconducting quantum dots exhibit different properties depending on their geometry. Different geometries are shown in Figure 7 (circular, asymmetric circular, square and triangular).

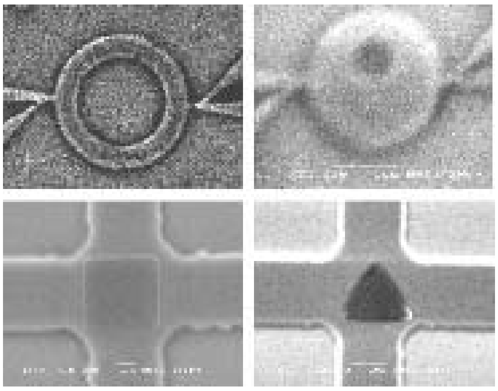


Figure 7 © M Morelle, V Moshchalkov, Belgium et al

It is not possible to engineer arrays of nanoparticles and quantum dots due to their sub microscopic size. Instead, these structures are “grown”. Continued intensive investigation of their growth and properties of these nanostructures is necessary for application to new technologies.

What are Josephson Junctions?

A Josephson junction consists of a very thin insulating layer (e.g. AlO_X) sandwiched between two superconducting materials (e.g. Nb), as shown in the diagram. A spontaneous current is created in the insulating contact between the two superconductors due to the overlapping of the two superconductors’ wavefunctions. This overlap allows a Cooper pair of two electrons to penetrate from one superconductor to another.

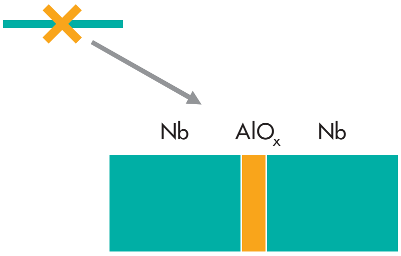
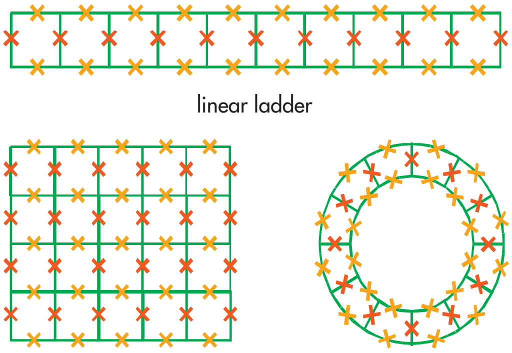


Figure 8 © A Ustinov, Germany

Exploring and understanding the structure and dynamics of low energy excitations in complex Josephson systems such as Josephson ladders, long Josephson junctions and others in different geometries and types of background will be crucial to development of new technologies.

Figures 9 and 10 show some of the systems we are interested in studying.



linear ladder

2D array

annular ladder

Figure 9 © A Ustinov, S Flach, Germany et al

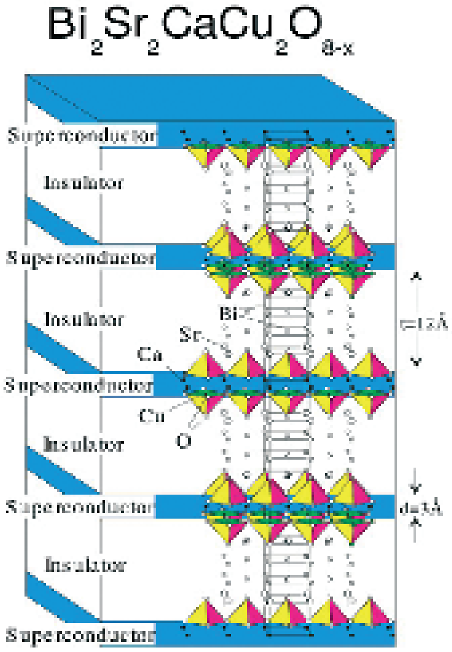


Figure 10: A stack of Josephson Junctions.
© N Pedersen, Denmark, G Filatrella, Italy

The behaviour of Josephson vortices (which occur in Josephson junctions) and other physical properties depends on the symmetry of the elementary cell in the Josephson junction array. Examples of different cell symmetries are shown in Figure 11: striped, zigzag and honeycomb dice lattice (above) and triangular array (below).

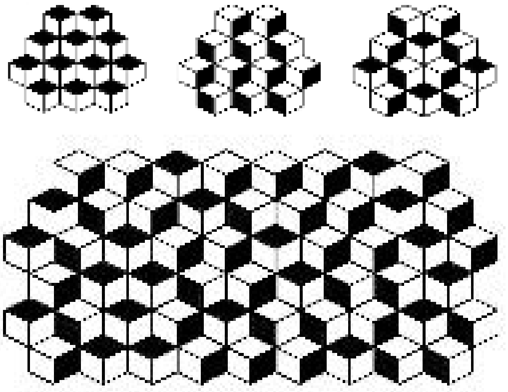


Figure 11 © P Martinoli, Switzerland

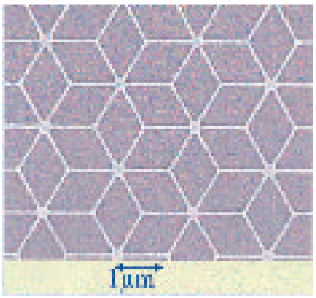


Figure 12 © P Martinoli, Switzerland

Similar behaviour arises in superconducting networks of metallic wires (depicted in Figure 12).

The transition from classical to quantum tunnelling, and tunnelling phenomena in general (as depicted in Figure 13), is an area not yet fully understood and needs further development.

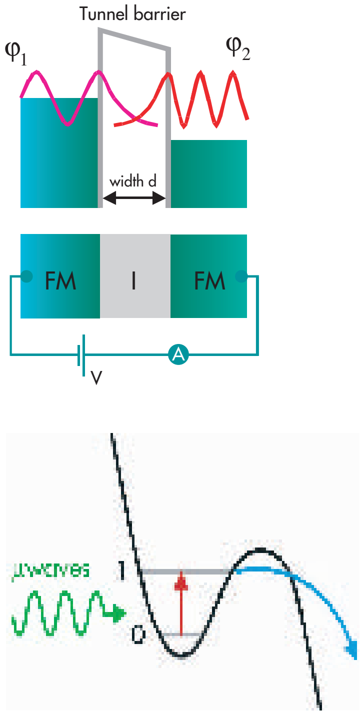


Figure 13 © A Barone, M Cirillo, Italy et al

Applications

Arrays of nanoparticles in organic matrices and quantum dots, as well as arrays of Josephson Junctions may have numerous practical and industrial applications as they are highly efficient and simple to use. Applications could be in quantum dot lasers, Magnetic Random Access Memory (MRAM, see Figure 14), Terahertz radiation sources and receivers / antennae, quantum computers (see Figure 15), biotechnology and nanomagnetism.

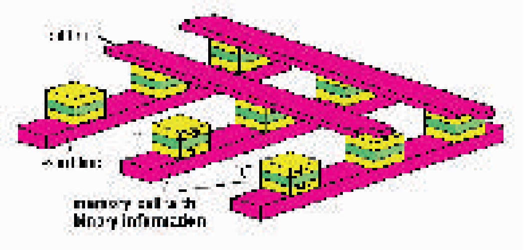


Figure 14: MRAM, made of three dimensional arrays of magnetic nanodisks.

© K. Kürten, Austria et al

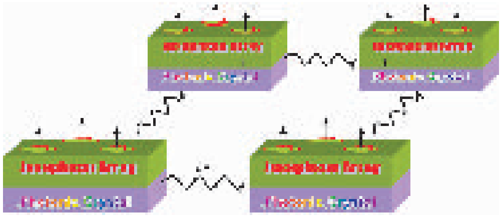


Figure 15: Building a working quantum computer consisting of a sandwich of Josephson junctions or an array of Josephson junctions and a microwave photonic crystal. These devices could be used as elementary building blocks for a quantum telecommunication network.

© F V Kusmartsev, UK et al

THz Radiation

THz radiation is potentially a very important area of research. This frequency gap is currently not being used, and in fact corresponds with the frequency of signals in the human brain. It may be that developing THz technology will help us to understand how the brain works. THz radiation is a lot less damaging than other rays, for example X-rays, yet it still has the ability to penetrate most materials. Possible usage could be to permanently scan things (for example in airports) without the danger of harmful radiation.

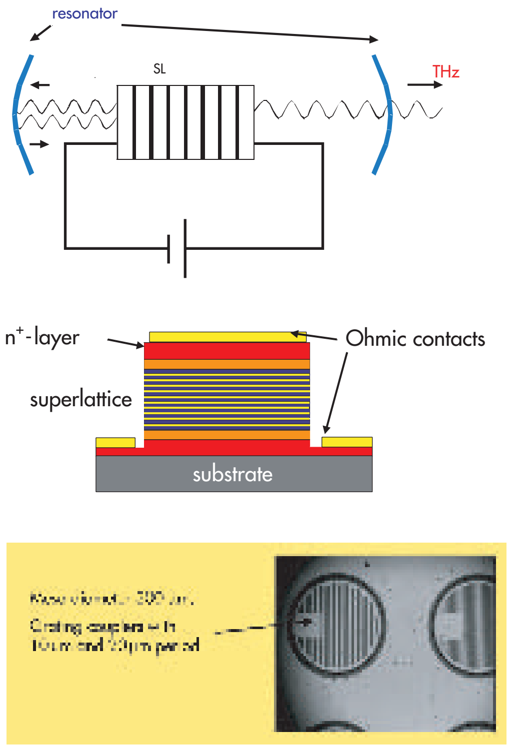


Figure 16: Development of new approaches for a THz generator with a semiconductor superlattice as the active element.

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Magnetic particles

A magnetic nanocomposite is a natural and/or artificial mixture of magnetic particles of nanometre sizes embedded into non-magnetic, insulating, semiconducting or metallic environments. Assemblies of small magnetic particles are formed by nature in many biological and geological systems (for example blood, soils and rocks). They can also be prepared artificially. Their magnetic characteristics are greatly enhanced due to finite size effects. This giant amplification of the sensitivity of such materials to external electromagnetic radiations means that they may be used in many unique applications. Magnetic and electrical properties (including electrical resistivity) and reflectivity may be changed by several orders depending on the particle sizes, separation and composition. These properties are applicable in magnetoresistive sensors and read heads, magnetic recording media, write heads and shielding and screening materials for heads and radars. Complex dynamical behaviour such as magnetization reversal (which has been recently observed when subject to intense short pulses of magnetic field) could revolutionise the technology of fast data flow, reading and writing information on hard disks and eventually be implemented for data storage systems of very high capacity. The analysis of such dynamical processes is an important new area of research.

Activities

Workshops

One workshop will take place each year for approximately 30-50 participants in different European countries, i.e. Croatia, Italy, Sweden, UK and others.

Conference collaboration

Occasionally this network will collaborate with an existing conference to allow for a wider scope of researchers to attend. The first one was a joint Conference with Japanese Physical Society, which took place in September 2005 in Crete.

Summer schools

Each year a summer school will be arranged with the first one being in June 2005 in Kiten, Bulgaria.

Exchange visits

Two types of grants for exchange visits are available:

- Short visit grants of up to 15 days
- Exchange grants, from 15 days to three or six months

Website

A homepage is maintained on the ESF website, in addition to the programme's own homepage which can be found at:
http://www-staff.lboro.ac.uk/~phrtg/aqdjj

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