Quantum superconducting nanowires

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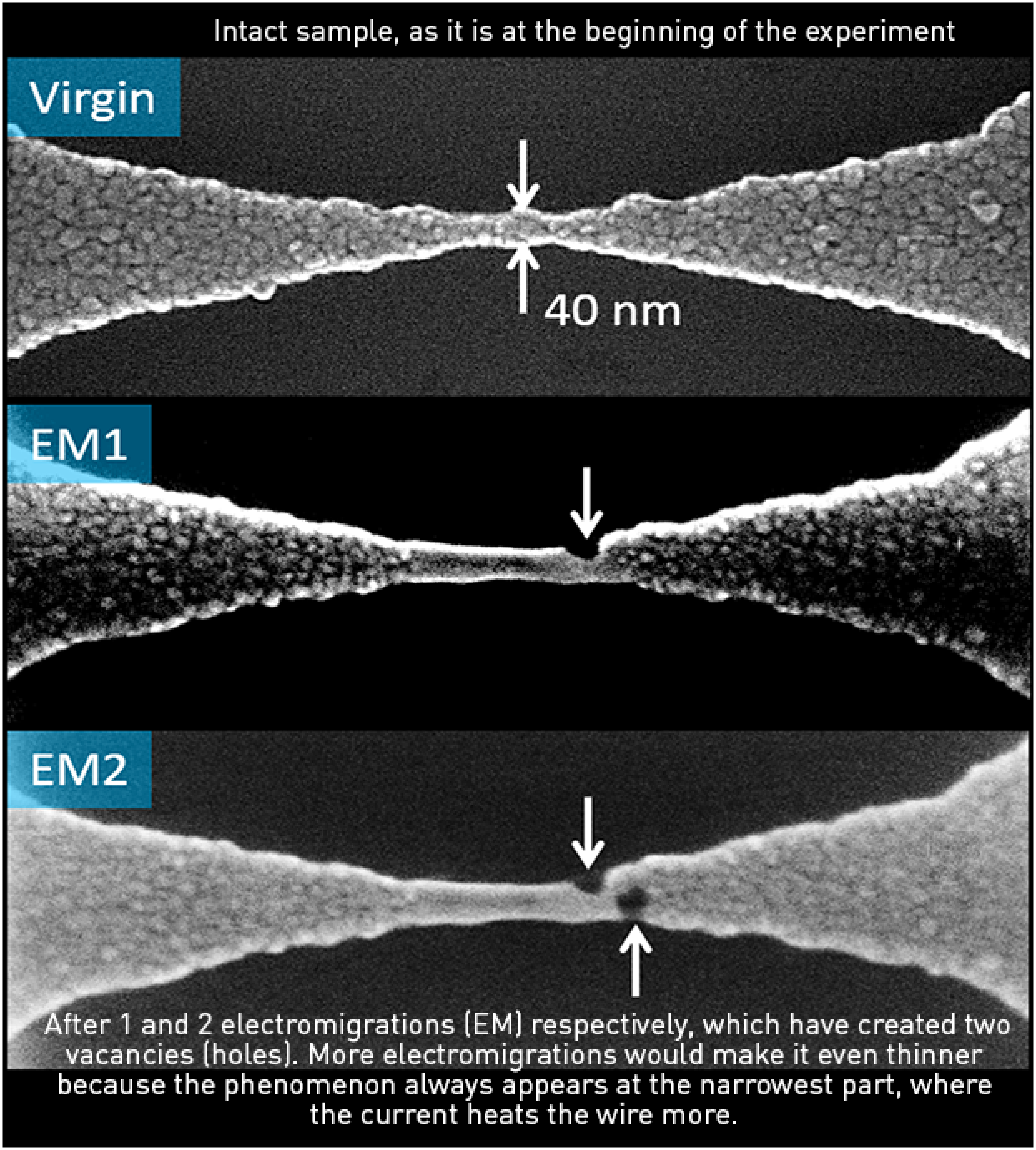
Various properties and phenomena that are unknown at our scale, appear instead at an atomic scale, opening the way for a new industrial revolution. Recent experiments performed on superconductors by Xavier Baumans, a PhD student at the University of Liège's Department of Physics, have established a limit beyond which nanowires permanently lose their superconductivity, even at very low temperatures. To achieve this, Xavier Baumans and his colleagues reduced the fabrication limit of these wires to the width of an atom! A major innovation, described in ***Nature Communications***, which will undoubtedly interest quantum computer designers.

An assistant lecturer at the University of Liège's **Physics Department** (**Materials Pole**, Professor **Alejandro Silhanek**), **Xavier Baumans** studies the behaviour of extremely small **superconducting** electronic circuits. In this case, "extremely small" means from 100 **nanometres** (100 nm or 100 millionths of a metre) up to… a few **atoms**. These circuits are much sought after since they are involved in the composition of quantum computers. "*Researchers already predicted then observed a strange phenomenon many years ago",* Xavier Baumans explains. "*If you reduce the size of devices too much, the superconductor effect can disappear!*" In fact, a double phenomenon was observed: fluctuations of the order parameter (switching from superconductivity to no superconductivity) appear in two forms: thermal and quantum. As their name indicates, the latter aren't due to temperature but to size, owing to the fact that the scale is that of an atom. Therefore, we can't do anything about them because they are intrinsic to the system: even by reducing the temperature close to **absolute zero**, they are always present.

However, the observations made so far had limits. One relates to the size of the wires studied: approximately no more than 30 nm. Another concerns the fact that the observations were made according to several different samples: the researchers would take a 90 nm wire, then a 60 nm one and so on, and estimate a bracket where superconductivity disappeared.



Intact sample, as it is at the beginning of the experiment

After 1 and 2 electromigrations (EM) respectively, which have created two vacancies (holes). More electromigrations would make it even thinner because the phenomenon always appears at the narrowest part, where the current heats the wire more.

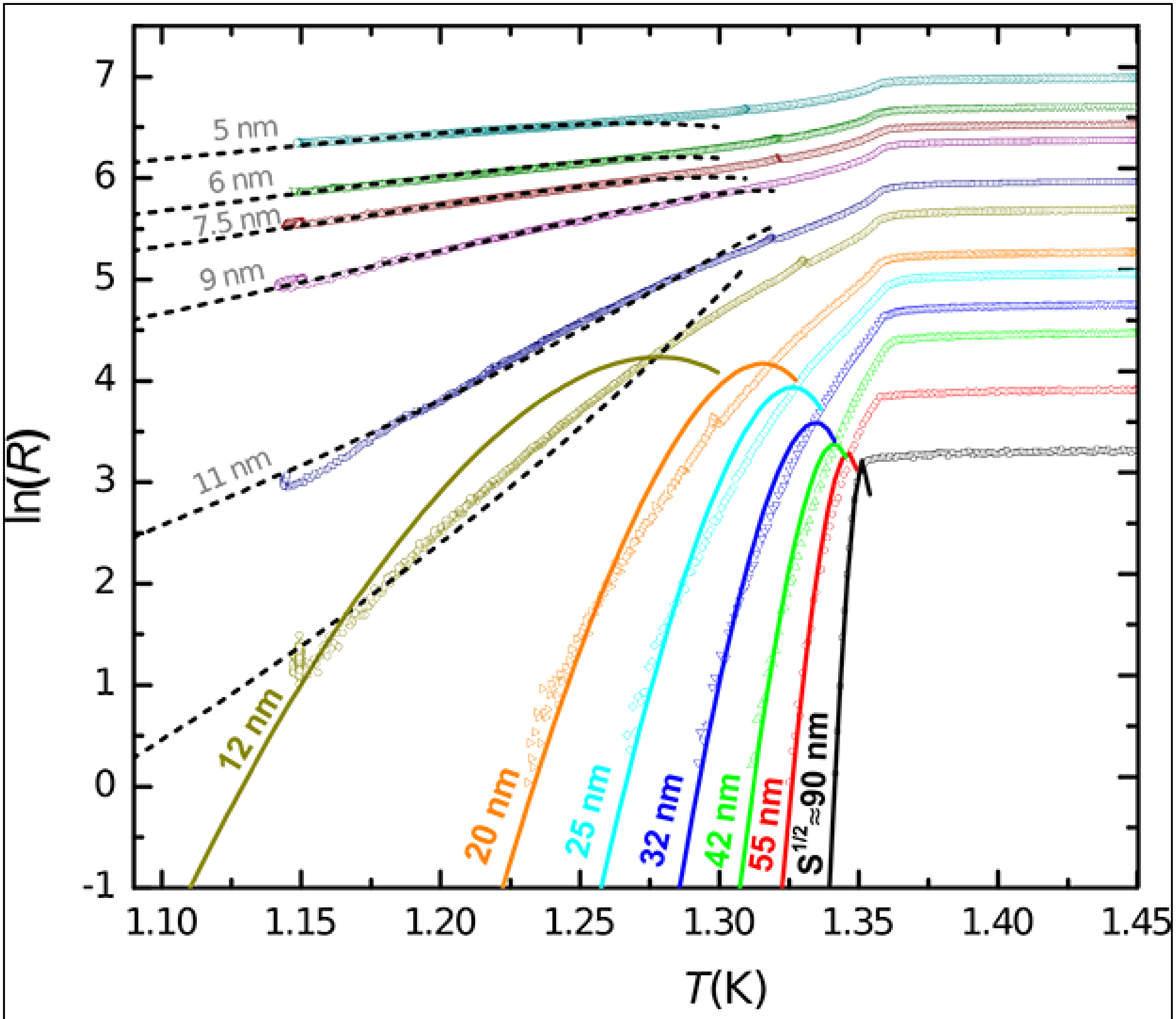
In all finesse

The goal of the research, whose results have just been published (1), was therefore to determine precisely at what size the material loses its superconducting properties and where the transition lies between thermal fluctuations and quantum fluctuations. To achieve this - and this is a major first - Xavier Baumans and his colleagues from ULg and KUL first reduced the wire's fabrication limit to less than one nanometre! "*It is important to realise that an atom is a tenth of a nanometre",* the young researcher tells us excitedly. "*A 10 nm wire is 100 atoms wide and a 1 nm wire is approximately 10 atoms wide*!" How can this be achieved? Thanks to the phenomenon of electromigration, which is normally destructive but in this case, it worked to the advantage of the researchers.

This happens when a current is applied to conducting wires, in this case, an aluminium wire. The current causes the metallic ions to migrate inside the wire and the phenomenon is self-sustaining and runs away. The smaller the size of the wire, the more the current heats the wire because it is thinner and, therefore, the ions migrate more and the size reduces further, and so on. This phenomenon limits the lifetime of electronic circuits. "*We used this to our advantage*", Xavier Baumans explains. "*We domesticated it by preventing runaway. A small current starts to make the ions migrate and reduces the size of the wire. If you're not careful, the wire can break in just a few seconds. By controlling it through a computer, we can regulate the current in the wire so that if we see indications of runaway, we can react in less than a thousandth of a second by reducing the value of the current in the wire; by doing this, we reduce the migration and the narrowing of the* *wire. Therefore, it is necessary to always maintain a sufficient current so that the ions migrate (otherwise, there is no reduction in the wire) but not too great so that the reaction doesn't run away (otherwise, the wire breaks)."* This is one of the research's major contributions: the perfect mastery of the process to continuously reduce the size of a conducting wire.

The 10 nm limit

Mastery with an immediate outcome, the research's second major result: the measurements can be performed on the same sample! The experiment began with a wire that was much larger in size than the estimated limit (i.e. a superconductor), which was then reduced in size through several stages. "*The width of the wire went from 70 nm to less than 10 nm and we managed to do better than that: at one point, we reduced the size of the wire to the width of one atom, i.e. the tenth of a nano*!" The curves indicating the results show that the wire has a certain resistance in its normal state. When the transition temperature is reached, the resistance drops to zero (superconductivity, in the case of a 70 nm wire).



The curves in solid lines and dotted lines represent two models: "thermal fluctuations" (solid) and "quantum fluctuations" (dotted). `
As of 12 nm (estimated width of wire) the thermal fluctuations no longer form the curve properly. This means that the quantum fluctuations are predominant.

For smaller widths, the transition temperature is no longer as well defined. The resistance decreases more slowly. As the wire becomes thinner, resistance decreases more slowly, until the point where it does indeed decrease, but never reaches 0 again. Hence, the wire is never a superconductor again. This phenomenon occurs if the width is approximately 10 nm. "*It's the limit between thermal and quantum fluctuations*", Xavier Baumans points out. "*As of this limit, the preponderant fluctuations are quantum. It doesn't matter how much you cool the circuit, its superconductivity will fade and disappear. Permanently*".

The precise determination of the threshold value beyond which superconductivity ceases is the third major contribution of this researcher's work. Because superconducting circuits are much sought after by designers of future quantum computers. "*Our research primarily serves as a warning*", Xavier Baumans adds. "*Superconductivity is essential but if we reduce the size of the circuits too much, this characteristic disappears… We have introduced a limit. Although, I imagine a way will be found to overcome this limit*".

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(1)*Thermal and quantum depletion of superconductivity in narrow junctions created by controlled electromigration,* Xavier D.A. Baumans et al. NATURE COMMUNICATIONS | 7:10560 | DOI: 10.1038/ncomms10560 |