technology to be widely and rapidly taken up across many biological disciplines. ∎

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CONDENSED-MATTER PHYSICS

# A solid triple point

**The observation of a triple point of coexistence between two insulating phases and a conducting phase in vanadium dioxide reveals physics that may help to unravel the role of electronic correlations in this material.** SEE LETTER P.431

**DOUGLAS NATELSON**

Much of condensed-matter physics is concerned with thermodynamic phases, their properties and their transitions. In correlated materials, the electron–electron and electron–lattice interactions result in a competition between various electronic, magnetic and structural phases. The transitions between competing phases can reveal information about the underlying states that is otherwise difficult to obtain. On page 431 of this issue, Park *et al.*[1] use a micromechanical device and single-crystal nanobeams to determine with high precision the tensile stress–temperature phase diagram of vanadium dioxide ($VO_2$), an archetypal correlated oxide. Their experiment reveals a surprising and interesting fact: the metal–insulator phase transition for which $VO_2$ is famous is in fact a triple point, a rare circumstance in which three phases (here two insulators and a metal) can coexist. The experiment also determines the entropy differences between the various phases — information crucial to a complete understanding of the transition.

When a large amount of a substance (such as water) is brought together, it may exist in distinct phases (such as solid, liquid and gas). At given conditions, for example at a particular pressure and temperature, the thermodynamically stable phase is the one with the lowest free energy, which is determined by the arrangement, motion and interactions of the constituents. A phase diagram is a map of the stable phases as a function of parameters such as pressure and temperature.

When two phases coexist stably, their free energies must be equal, and for a single species, this condition leads to a coexistence 'line' for the two phases in the phase diagram. For example, ice and liquid water coexist in equilibrium at 0 °C and atmospheric pressure, and increasing the pressure decreases the melting point. Similarly, liquid water and water vapour coexist stably at 100 °C
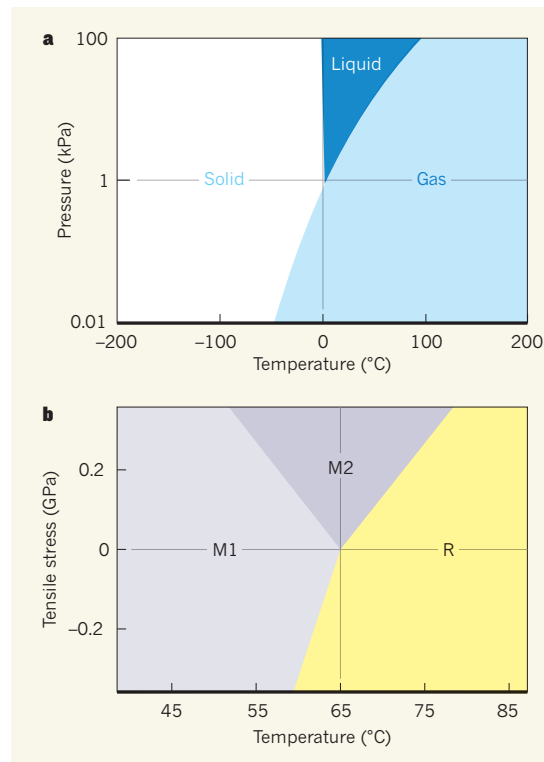


**Figure 1 | Phase transitions with triple points. a,** The phase diagram of water. At only one pressure and temperature can solid, liquid and gaseous water coexist in equilibrium. This triple point defines the Kelvin temperature scale. **b,** Park *et al.*[1] have mapped the phase diagram of vanadium dioxide. The triple point at zero tensile stress and the slopes of the phase boundaries greatly constrain theories that seek to understand the transitions from metal (R) to insulator (M1 or M2) in this material. Part **b** is based on Fig. 4b of the paper.

and atmospheric pressure, with decreasing pressure reducing that temperature (hence water boils at a lower temperature on top of a mountain than at sea level). These two coexistence curves can intersect only at a single value of pressure and temperature — a triple point (Fig. 1a). For water, this happens at 0.01 °C and 612 pascals. This particular triple coexistence defines the Kelvin temperature scale[2].

In $VO_2$, the competing phases of interest are all solids, albeit with different lattice structures and electronic properties: a high-temperature metallic phase (with a rutile lattice structure, R), and two insulating phases (with monoclinic structures, M1 and M2). The competition between these phases is of great interest because of the marked change in electronic and optical properties that occurs at the metal–insulator transition, the proximity of the transitions to room temperature, and the need to better understand the underlying physics. The relative importance of electron–electron interactions (Mott physics) and lattice distortion (Peierls physics) in stabilizing the M1 phase has been debated for decades. In addition to temperature, the intensive quantity relevant to $VO_2$ is the tensile stress rather than the pressure. Controlling this stress makes measurements in bulk crystals and thin films challenging.

Single-crystal $VO_2$ nanobeams[3] with a well-defined tensile-stress profile along the beam have been a boon to those trying to understand the intrinsic physics of this material. Park *et al.* attached an individual single-crystal $VO_2$ nanobeam to bridge a notched silicon structure, and used a piezo actuator to apply a controlled longitudinal deformation to the nanobeam, and so vary its length. Through polarized optical microscopy, Raman microscopy and electrical measurements, they identified regions of the suspended beam in the M1, M2 and R phases. Because the entire system was mounted on a temperature-controlled stage, the authors were able to determine the tensile stress–temperature phase diagram (Fig. 1b) by performing measurements of phase composition as a function of temperature at fixed length (which they can relate to the stress) and as a function of length at fixed temperature. To obtain measurements at zero stress, they broke

the nanobeam to ensure that the remaining suspended portions, which were no longer in contact, were stress free.

By mapping the phase diagram with high precision, the authors extracted interesting clues that constrain theoretical treatments of the phases in this system. First, it turns out that the M1, M2 and R phases can all coexist at a triple point at 65.0 °C that coincides with zero applied stress. There is no obvious reason why the M2 phase should become thermodynamically stable as soon as the tensile stress exceeds zero, as Park *et al.* observed. This fact, long obscured by lack of control over sample stresses, is something that a microscopic theory should explain. Second, the authors determined the ratio of the resistivities of the two insulating phases, a parameter that in clean crystalline material is related to the densities of states at the energy of the highest occupied electronic states and the effective masses of the electrons, quantities that should be calculable using electronic-structure methods. Finally, they determined the entropy difference per $VO_2$ group between the metallic phase and each insulating phase at the triple point. Although first-principles electronic-structure calculations are challenging, particularly when trying to understand effects at temperatures far above absolute zero, some future computational approach should be able to assess the relative contributions of electronic and structural degrees of freedom to these differences,

further illuminating the role of electronic correlations in the transition(s).

Many other correlated systems exhibit similar phase competitions, including the manganites[4] and the rare-earth nickelates[5]. The current work shows the power of measurements that can combine micrometre- or nanometre-scale single-crystal materials, control of the stress and strain, spatial mapping of phases and *in situ* electronic transport. The importance of material quality and stresses (for example due to lattice mismatch of a film with a substrate) have long been known, and studies of bulk samples under applied and chemical pressure have been revealing in some correlated systems[6]. With the synthesis of novel structures and experimental methods such as those described here, the prospects are bright for new insights into these incredibly rich, complex materials. ∎

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# Sweet enticements to move

**The formation of new blood vessels from pre-existing ones is a carefully orchestrated dance. A study reveals that the metabolism of sugar by glycolysis contributes to its regulation.**

**CHOLSOON JANG & ZOLTAN ARANY**

The breakdown of fuel by metabolism is the engine that sustains all cellular activities. But can metabolism also steer and control cellular processes? Writing in *Cell*, De Bock *et al.*[1] suggest that the answer is yes, at least in the context of glucose metabolism and angiogenesis — the formation of new blood vessels*.

Glycolysis is the cellular process by which glucose is converted into pyruvate. A cell then makes a choice: it can convert pyruvate to lactate, which exits the cell, for a net yield of 2 ATP molecules (the currency of cellular energy transfer) or, in the presence of oxygen, the pyruvate can enter cellular organelles

called mitochondria and become fully oxidized, producing a net yield of more than 30 ATP molecules. One would not expect any oxygenated cell to opt out of this mitochondrial bonanza, but some do, in a phenomenon first noted[2] in cancer cells by Otto Warburg in 1956. Cancer cells probably make this choice because intermediate molecules formed during glycolysis support the synthesis of macromolecules needed for cellular replication[3]. But do any non-cancerous or even quiescent cells also display the Warburg effect? Endothelial cells, which line blood vessels throughout the body and mediate angiogenesis, do[3], but until now little was known about how metabolism

*This article and the paper under discussion[1] were published online on 14 August 2013.