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Markus B. Raschke

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Quantum Mineralogy: Why does nature rarely produce minerals with unusual quantum properties, and what are these anyway?

MARKUS B. RASCHKE
Department of Physics and JILA, Materials Science and Engineering Program, and Center for Experiments of Quantum Materials,University of Colorado, Boulder, CO 80303
markus.raschke@colorado.edu

"Mineralogy is dead" is often heard as a complaint in acedemia, with few geology departments at universities, federal agencies, or national labs still hiring faculty and staff in this traditional and once so vibrant field. However, the field has not only historically been foundational for different areas of science, but it lives on, and is even of growing importance in materials science and solid-state physics – fields which emerged almost directly from mineralogy. Mineralogy as a discipline has established the principles of crystal chemistry, crystal structure, and crystallographic symmetry based on minerals in the absence of synthetic analogues. Diamond (C), Rocksalt (NaCl), and sphalerite (ZnS) to this day serve as canonical examples of crystalline solids to teach crystal structure and chemical bonding in every condensed matter physics textbook.

Materials science and condensed matter physics evolved, inspired by mineralogy based on the observations of a wide range of interesting properties of minerals, such as magnetism of magnetite, optical birefringence of calcite, piezoelectricity of quartz, or pyroelectricity of tourmaline. With these properties of minerals quickly finding practical and industrial applications, the extension to solid state chemistry and materials synthesis then opened the door to make minerals artificially, with higher purity and better crystal quality. This also opened the door to synthesize new materials that are not found naturally in search for new properties.

This approach has been a hugely successful endeavor, with the first industrial revolution based on iron, steel, and alloys, and the second based on silicon as semiconductor for electronics and photovoltaics. In parallel, solid-state physics grew into the largest sub-field of physics with the discovery of a plethora of so-called quantum phenomena in crystalline materials. Effects like colossal magnetoresistance, high-temperature superconductivity, heavy fermion behavior (which are properties where the electrons appear to have a mass much higher than their original single particle mass), metal-insulator transitions, strange metals, complex magnetic order, topological phases, and in fact controllable phase transitions between these quantum phases have led to numerous Nobel Prizes.

However, while, e.g., natural perovskite ($CaTiO_3$) does not exhibit any interesting quantum phenomena, it is the parent compound for a range of synthetic derivatives, which by contrast host a wide range of such quantum phenomena. So why do most natural minerals, even when structurally and chemically similar to synthetic quantum materials, not exhibit these unusual quantum phases?

Rock forming minerals; the bulk of minerals that make up the earth crust are silicates and oxides of light elements, which makes them simple insulators. Their electronic and atomic structures are well understood, and described by simple quantum mechanics or even classical models. But one common mineral stands out in a distinct way, with the heavy transition metal element iron, and where its electron spin comes into play: Magnetite (Fe_3O_4). Magnetite and its magnetism (ferrimagnetism in this case) is a quantum phenomenon, which relies on the quantized nature of the electron spins and their interaction, which cannot be explained classically. However, purity and crystal quality of natural minerals are an issue. Minerals grow from fluids of selectively enriched but always mixed composition, and under poorly controlled and often variable

pressure and temperature conditions during crystal growth. This inevitably leads to chemical heterogeneity, incorporation of impurity atoms, and accumulation of structural defects – processes which make minerals often aesthetically appealing but typically interfere with electron correlation or magnetic order and the formation of exotic quantum states. This situation is particularly dramatic with rare earth element (REE) minerals. Indeed, a large number of quantum materials gain their unique characteristics from the unique electronic and spin properties of REE. However, in nature, because of their chemical similarity, geochemical processes cannot sufficiently separate the different REE into different minerals. At best a preference towards lighter (LREE) or heavier elements (HREE) will result in enrichments of one or the other. Therefore, without the complex artificial processes of REE separation, the formation of selective REE materials, like the strong permanent magnets $Nd_2Fe_{14}B$ or $SmCo_5$, in nature is very unlikely.

In this talk I will illustrate the physical basis of quantum materials and how this field emerged from mineralogy. Why nature generally fails, yet with notable exceptions succeeds to provide minerals with exotic quantum properties, discussing in particular the following examples:

Van der Waals materials: Micas, graphite, and molybdenite (MoS_2) are perhaps the most prominent examples of minerals with sheet structures, characterized by strong intra-layer connectivity and weak inter-layer Van der Waals bonding. Especially graphite and the different transition metal dichalcogenides (e.g., MX_2, with M=Mo,W, X=S, Se) can easily be exfoliated even using regular stationery grade adhesive tape to single monolayer thickness. These and related materials have become a laboratory for the discovery and control of many exotic quantum phenomena such Berry phases, Quantum Hall effect, Mott transitions etc. These discoveries triggered a wider recent search for material candidates, and it was found that even the natural and common clay mineral vermiculite $(Mg,Fe^{2+},Fe^{3+})_3[(Al,Si)_4O_{10}](OH)_2\square 4H_2O$ is both a semiconductor as well as an antiferromagnet (Pacakova, 2025).

Superconductivity: Besides the most prominent property of superconductivity, where in below a critical temperature T_C, the electrical resistance abruptly drops to zero, another characteristic is that a magnetic field is expelled from within the material (Meissner effect). Superconductivity is fundamentally a quantum mechanical effect and occurs in certain metals (Hg, Pb, Nb, etc.), alloys, a wide range of transition metal oxides, notably cuprates, pnictides, MgB_2, and was recently discovered also in a bilayer of graphite and in solid H_2S at a very high pressure. While typically studied in synthetic compounds, the wide range of materials that exhib-

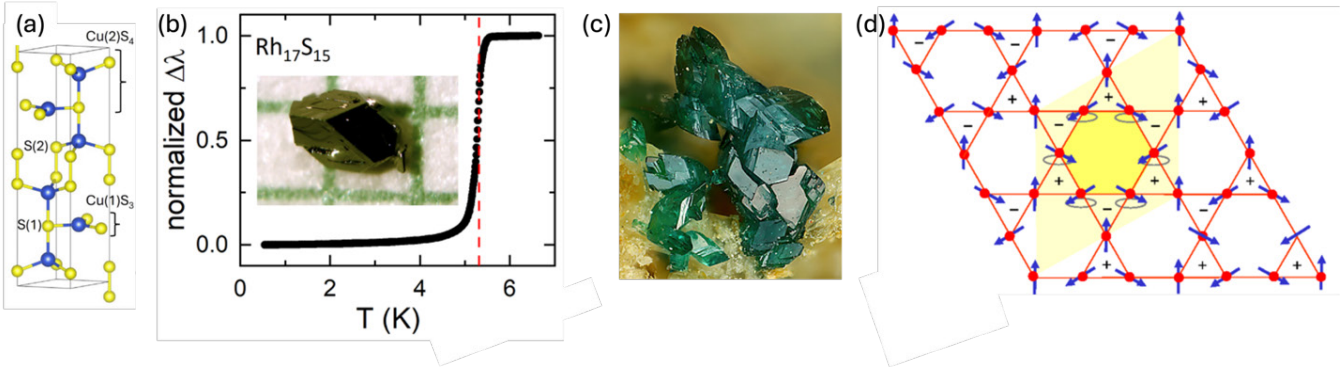

Figure 1. (a) Crystal structure of the natural superconductor covellite (CuS) (Antezak, 2025). (b) Single crystal and superconducting phase transition of miassite ($Rh_{17}S_{15}$) (Kim, 2024) at T_C showing the associated change in penetration depth of a magnetic field as a characteristic property of superconductivity. (c) Herbertsmithite ($Cu_3Zn(OH)_6Cl_2$) San Francisco Mine, Antofagasta, Chile (Elmar Lackner photo, FoV ca.1 mm, mindat:1128167).(d) illustration of so-called spin frustration on a kagome lattice with no long-range magnetic order as condition for a quantum spin liquid (Yildrim and Harris, 2006).

it superconductivity under certain conditions would suggest that some natural superconducting minerals may exist.

Indeed, with a critical temperature of 1.6 K, ***covellite*** (CuS) (Fig. 1a) was discovered as the first naturally occurring non-metallic superconductor (Di Benedetto, 2006). Despite its simple chemical formula, covellite is structurally complex featuring two inequivalent Cu and S sites, mixed valence of Cu, and a second-order structural phase transition at 55 K (Antezak, 2025). In fact, covellite's mixed valence resembles the physics of high-T_C cuprate superconductors.

A particularly exciting recent discovery is that of superconductivity in ***miassite*** ($Rh_{17}S_{15}$), a mineral discovered in isoferroplatinum (Pt_3Fe) deposits (Fig. 1b). Although its superconductive properties have been studied in lab-grown single crystals of that mineral, to eliminate Fe, Ni, Pt, and Cu impurities present in the natural samples (Kim, 2024). What makes this discovery significant is that miassite is a so-called 'unconventional' superconductor, exhibiting several anomalous properties, and for which no conclusive quantum theoretical description has yet been found (a Nobel Prize awaits). To date, only two other minerals where synthetic analogues exhibit superconductivity are known: ***parkerite*** ($Ni_3Bi_2S_2$) and ***palladseite*** ($Pd_{17}Se_{15}$), which is isostructural to miassite.

Quantum spin liquids: while ordinary magnetism is defined by long range order of electron spins quantum spin liquids exhibit the opposite. These are approximately described by rapidly fluctuating spin disorder. This is similar H_2O molecules in crystalline ice vs. liquid water, which are characterized by ordered vs. disordered states of water molecules. Quantum spin liquids are a very exotic quantum state of matter, originally hypothesized in theoretical condensed matter physics in the 1970s, and with many of the fundamental properties still occupying the minds of theoretical physicists. Incidentally, a mineral, namely ***herbertsmithite*** ($ZnCu_3(OH)_6Cl_2$) (Fig. 1c) is considered the first candidate material believed to host a quantum spin liquid (Norman 2016). In herbertsmithite, the copper ions form layers with a triangular Kagome lattice, separated by nonmagnetic intermediate layers of Zn and Cl – these structural conditions that are favorable for the formation of a quantum spin liquid phase (Fig. 1d). Investigations of this material for over a decade have discovered several intriguing physical phenomena, with work branching into the wider range of related minerals of the atacamite group.

I will conclude with some general criteria of structure, composition, and valence state, for which certain classes of minerals in their natural form could be candidates exhibiting unusual quantum behavior, or inspire corresponding synthetic efforts.

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