The Very Short Introductions Podcast
Episode 77: Condensed Matter Physics

The VSI Podcast Intro 00:07
Welcome back to The Very Short Introductions Podcast. From public health to Buddhist ethics, soft matters to classics, and art history to globalization, we'll showcase a concise and original introduction to a wide range of subjects, for wherever your curiosity may take you. So here is today's very short introduction.

Ross McKenzie 00:27
I'm Ross McKenzie. I'm an emeritus professor of physics at the University of Queensland, in Brisbane, Australia. And I've spent the past 40 years learning, teaching and researching condensed matter physics. I really love this Very Short Introduction series. And so I'm delighted that I can share my experience by writing Condensed Matter Physics: A Very Short Introduction. What is condensed matter physics? Well, it's all about states of matter. At school, you were probably taught that there are only three states of matter: solid, liquid, and gas. But this is wrong. There are many more states such as liquid crystal, glass, superconductor, ferromagnet, and superfluid, and new states of matter are continually, and often unexpectedly, being discovered. Condensed matter physics investigates how the distinct physical properties emerge from the atoms of which material is composed.

Ross McKenzie 01:38
How did I first get interested in condensed matter physics? Well, after I finished an undergraduate degree in theoretical physics in Australia back in 1982, I wouldn't have been able to answer this question, what is condensed metaphysics, even though it's the largest subfield of physics. I then went to Princeton University in the USA to pursue a PhD, and I took an exciting course on condensed matter and began to interact with students and faculty who were working in the field. At Princeton was Phil Anderson, who had won a Nobel Prize in Physics for some of his work in condensed matter. At the time, I didn't appreciate his much broader intellectual legacy. In his recent biography of Andersen, Andrew Zangwill states, quote, "More than any other 20th century physicist, Anderson transformed the patchwork of ideas and techniques, formally called 'solid state physics,' into the deep, subtle, and intellectually coherent discipline known today as 'condensed matter physics.'" Now, several decades after my PhD, my work became richer, as Anderson gave me an appreciation of the broader scientific and philosophical significance

of condensed matter physics, particularly its connection to other sciences, such as biology, economics, and computer science. And I'll say more about that later.

Ross McKenzie 03:18
But some of the bigger questions are when the quantitative differences become qualitative differences? And can simple models describe rich and complex behavior? What's the relationship between the particular and the universal? And how are abstract ideas related to concrete materials? So what are the key aspects of condensed matter physics that I would like everyone to know?

Ross McKenzie 03:50
Well, first, there are many different states of matter. It's not just solid, liquid, and gas. Consider the liquid crystals that are the basis of LCDs, liquid crystal displays, in the screens of televisions, computers, and smartphones. How can something be both a liquid and a crystal? Well, a liquid crystal is a distinct state of matter. And it has some properties like a liquid and some properties like a crystal. Now solids can be found in many different states. In everyday life, ice simply means solid water, but in fact, there are actually 18 different known solid states of water depending on the temperature of the water and the pressure that is applied to the ice. And in each of these 18 states, there is a unique spatial arrangement of the water molecules and there are qualitative differences in the physical properties of the different solid states. Condensed matter physics is concerned with characterizing and understanding all the different states of matter that can exist. Now these different states are called "condensed" states of matter, because the word condensed is used here in the same sense as when we say that steam condenses into liquid water. Now, generally, as the temperature is lowered or the pressure is increased, a material can condense into a new state of matter. And qualitative differences distinguish the many different states of matter. And these differences are usually associated with differences in symmetry and the type of ordering of the atoms.

Ross McKenzie 05:45
The second thing I'd like you to know, is that condensed matter physics involves a particular approach to understanding properties and materials. Now, every day we encounter a diversity of materials: liquids, glass, ceramics, metals, crystals, magnets, plastics, semiconductors, and foams. So these materials look and feel different from one

another. Their physical properties vary significantly. Are they soft and squishy or hard and rigid? Shiny, black, or colorful? Do they absorb heat easily? Do they conduct electricity well?

Ross McKenzie 06:29
Now, the distinct physical properties of different materials are central to their use in technologies around us, smartphones, alloys, semiconductor chips, computer memories, cooking pots, magnets in MRI machines, LEDs in solid-state lighting and fiber-optic cables. But why do different materials have different physical properties? Materials are studied by physicists, chemists, and engineers, but the questions, focus goals, and techniques of researchers from these different disciplines can be quite different. Now, the focus of condensed matter physics is on states of matter, and as a research field, it's not just defined by the objects that it studies—that is states of matter in materials—but rather by a particular approach to the study of these objects. And the aim is to address fundamental questions, and to find unifying concepts and organizing principles that can describe a wide range of phenomena in materials that are chemically very different from one another, and often structurally, as well.

Ross McKenzie 07:49
But the central question of condensed matter physics is how do the properties of a state of matter emerge from the properties of the atoms in the material and their interactions? And this idea of emergence is very important, and I'll come back to later. But let's consider a concrete example, that of graphite, and diamond. While you'll find very cheap graphite in lead pencils, you'll find diamonds in jewelry. Now both graphite and diamond are composed solely of carbon atoms, and they're both solid. But why do they look and feel so different? Graphite is common, black, soft, and conducts electricity moderately well. In contrast, diamond is rare, transparent, hard, and conducts electricity very poorly. Now, we can zoom in down to the scale of individual atoms using X rays, and discover the spatial arrangements of the carbon atoms relative to one another. And turns out, these arrangements are qualitatively different in diamond and in graphite. So diamond and graphite are distinct solid states of carbon, and they have qualitatively different physical properties at both the microscopic, or atomic level, and at the macroscopic scale.

Ross McKenzie 09:21

Third, I want you to know about superconductivity, one of the most fascinating states of matter. I've worked on it many times over the past 40 years. Superconductivity occurs in many metals when they're cooled down to extremely low temperatures, close to absolute zero—that's minus 273 degrees Centigrade. Now in the superconducting state, a metal can conduct electricity perfectly, that is perfectly, without generating any heat at all. The superconducting state also has a unique property, in that it expels magnetic fields, meaning that you can levitate objects, whether sumo wrestlers or trains. The discovery of superconductivity in 1911 presented a considerable intellectual challenge. What is the origin of this new state of matter? How do the electrons in the metal interact with one another to produce a perfect conductor, a superconductor?

Ross McKenzie 10:30
Now, many of the greatest theoretical physicists of the 20th century took up this challenge, but failed. The theoretical puzzle was only solved 46 years after the experimental discovery. Now, the theory turns out also to be relevant to liquid helium, nuclear physics, neutron stars, and elementary particle physics, including the Higgs boson. Now, new superconducting materials and different superconducting states continue to be discovered. And the Holy Grail is to find a material that can superconduct at room temperature. Now, I find superconducting even more interesting when considering quantum theory. Now, by 1930, it was widely accepted that quantum theory, in all its strangeness, could describe the atomic world of electrons, protons, and photons. However, this strangeness does not show itself in the everyday world of what we can see and touch. You cannot be in two places at the same time, your cat is either dead or alive. However, condensed matter physicists have shown that the boundary between the atomic and everyday world is not so clear cut. A piece of superconducting metal can take on some weird quantum properties, just like a single atom, even though the metal is made of billions of billions of atoms. It can be put in two quantum states at the same time, almost like Schrödinger's famous cat that was dead and alive at the same time.

Ross McKenzie 12:16
Fourth, condensed matter physics is all about emergence, the whole is greater than the sum of the parts. A system composed of many interacting parts can have properties that are qualitatively different from the properties of the individual parts. Water is wet, but a single water molecule is not. Your brain is conscious, but a single neuron is not. And such

emergent phenomena occur in many fields from biology, to computer science, to sociology, leading to rich intellectual connections with condensed matter physics. And condensed matter physics is arguably the field with the greatest success of understanding emergent phenomena in complex systems, particularly at the quantitative level. And there's been many, much cross-fertilization of ideas between the fields because of this common interest in emergence. But the success of condensed metaphysics is not because condensed matter physicists are smarter than sociologists, economists, or neurosciences; it's because the materials we study are just made of atoms, and they're much simpler than societies, economies, and brains.

Ross McKenzie 13:46
Finally, condensed matter physics is one of the largest and most vibrant subfields of physics. For example, in the last 30 years, the Nobel Prize in Physics have been awarded 13 times for work in condensed matter. And in the past 20 years, eight condensed matter physicists have received a Nobel Prize in Chemistry, again showing this cross-fertilization. So I hope I've sparked your interest in condensed matter physics, and I invite you to learn more about why I consider this field of science so significant, beautiful, and profound.

The VSI Podcast Outro 14:27
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