Study finds physical link to strange electronic behavior

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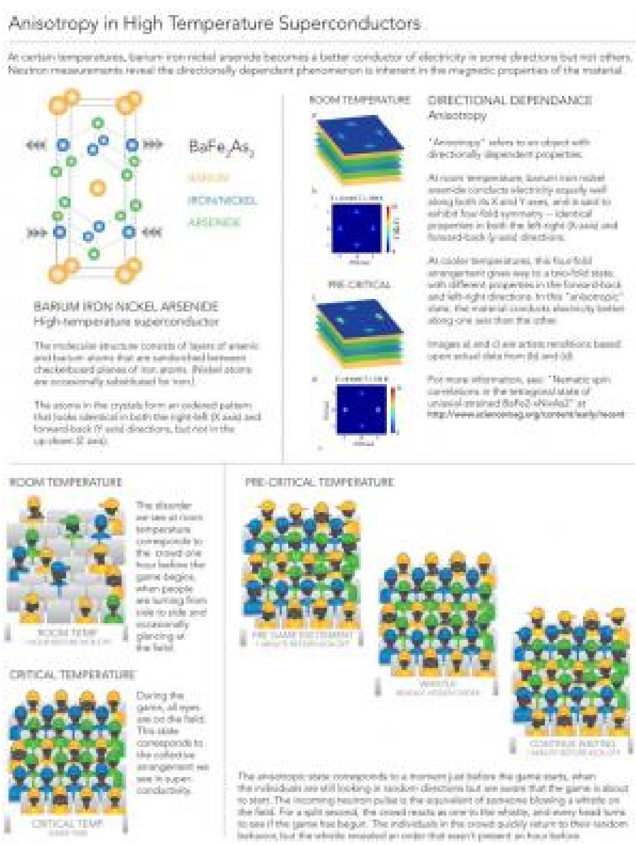

Inelastic neutron scattering experiments revealed a temporary, collective anisotropic order prior to the onset of magnetism in a temperature interval where anisotropic resistance had previously been measured. Credit: Tanyia Johnson/Rice University

Scientists have new clues this week about one of the baffling electronic properties of the iron-based high-temperature superconductor barium iron nickel arsenide. A Rice University-led team of U.S., German and Chinese physicists has published the first evidence, based on sophisticated neutron measurements, of a link between magnetic properties and the material's tendency, at sufficiently low temperatures, to become a better conductor of electricity in some directions than in others.

The odd behavior, which has been documented in a number of materials, occurs at temperatures slightly higher than those needed to bring about magnetism; magnetism is believed to be essential for the origin of high-temperature superconductivity. In a new study appearing online this week in the journal *Science Express*, scientists at Rice, the Chinese Academy of Sciences in Beijing and Germany's Technische Universität München (TUM) offer the first evidence that the directionally dependent behavior arises from inherent physical properties of the material rather than from extraneous impurities, as had been previously suggested.

The new findings are based on sophisticated inelastic neutron-scattering experiments performed on several samples of barium iron nickel arsenide at the PUMA triple axis spectrometer at TUM's Heinz Maier-Leibnitz Zentrum in Garching, Germany. The research team said they hope the findings will prove useful in explaining the underlying physics of directionally dependent electronic phenomena that have been observed in several different types of superconducting materials.

"Most high-temperature superconductors, and many closely related compounds, exhibit a number of exotic electronic phases, particularly as they approach the critical temperature where superconductivity arises," said Pengcheng Dai, professor of physics and astronomy at Rice and the study's senior corresponding author. "Inelastic neutron scattering and other techniques are now allowing us to explore the physical basis of many of these phases."

Explaining high-temperature superconductivity remains the foremost challenge in condensed matter physics. First documented in 1986, the phenomenon is marked by zero electrical resistance in some crystalline ceramic materials below a critical temperature. While very cold, the critical temperatures for high-temperature superconductors—between 50 and 150 kelvins above absolute zero—are relatively high in comparison with the temperatures required for conventional superconductivity.

Like most high-temperature superconductors, barium iron nickel arsenide is a composite crystal. Its molecular structure consists of layers of arsenic and barium atoms that are sandwiched between checkerboard planes of iron atoms. The nickel atoms are then partially substituted for iron to tune the material's physical properties. The atoms in the crystals form an ordered pattern that looks identical in both the right-left (x-axis) and forward-back (y-axis) directions, but not in the up-down (z-axis).

At room temperature, the material acts as one might expect, conducting electricity equally well along both its x-axis and y-axis. However, as the material is cooled to near the critical temperature for magnetism, it passes through a phase where electrical resistance is higher in one direction than the other. Physicists call directionally dependent behavior "anisotropic resistance."

In the new study, Dai and colleagues bombarded crystals of barium iron nickel arsenide with neutrons. Neutron-scattering measurements can reveal the molecular structure of materials in great detail, and inelastic neutron-scattering tests allow physicists to see, among others, the vibrational properties of materials. In the magnetic inelastic scattering experiment at TUM, the incoming neutrons brought about short-lived magnetic waves in the crystals. Surprisingly, the intensity of these magnetic waves turned out to be different in the x and y directions. The experiments revealed that this directional dependence of magnetic excitations in the barium iron nickel arsenide occurs at precisely the same temperature range as the anisotropic resistance, thus establishing a crucial link between the two phenomena.

Rice theoretical physicist and study co-author Andriy Nevidomskyy, assistant professor of physics and astronomy, used the analogy of a crowd gathered at a stadium to watch a sporting event.

"During the game, all eyes are on the field, and this is an ordered state that describes all the individuals in the crowd in relation to one another," he said. "This state corresponds to the collective arrangement of electrons we see in magnetism and in superconductivity. The disordered arrangement we observe at room temperature, on the other hand, corresponds to the chaos we would see in the crowd one hour before the game begins, when people are turning from side to side and occasionally glancing at the field.

"The anisotropic state found in our study corresponds to a moment just before the kickoff, when the individuals are still looking in random directions but are aware that the game is about to start," Nevidomskyy said. "The incoming neutron pulse is the equivalent of someone blowing a whistle on the field. For a split second, the crowd reacts as one to the whistle, and every head turns to see if the game has begun. The individuals in the crowd quickly return to their random behavior, but the whistle has revealed an order that wasn't present an hour before."

The inelastic neutron scattering experiments uncovered an analogous behavior in the barium iron nickel arsenide. At high temperatures, the pulse of energy revealed no underlying order. The temporary, collective anisotropic order occurred only in the brief temperature interval prior to the onset of magnetism where the anisotropic resistance had previously been measured.

Rice theoretical physicist Qimiao Si, another study co-author, said the magnetic behavior observed by the inelastic neutron-scattering measurements reflects the way the spins of the electrons are dynamically organized in the material.

"This spin excitation anisotropy sheds new light on the microscopic origins of electronic phases in the iron pnictide superconductors," said Si, Rice's Harry C. and Olga K. Wiess Professor of Physics and Astronomy. "It may help explain the interplay between magnetism and superconductivity and, more generally, the mechanism for superconductivity, in the iron pnictide superconductors."

Provided by Rice University

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