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Norman Mannella's NSF CAREER Research Imposes Coherence on Complex Systems

From Cross Sections, the Physics Department Newsletter, *Spring 2012 issue*

Watch a herd of horses galloping at full speed and try to calculate when each individual hoof hits the ground. That's the kind of challenge Assistant Professor Norman Mannella is up against, in a scientific sense, when he studies complex electron systems. With a $600,000 Faculty Early Career Development (CAREER) grant from the National Science Foundation, he has additional support to meet that challenge for the next five years.

The CAREER program sponsors the foundation's most prestigious awards for junior faculty who exemplify outstanding research and teaching and work to integrate the two within their respective institutions. When Mannella joined the physics faculty in August 2007, he began building a research program dedicated to studying novel materials -- new and improved materials that can be altered by design to meet needs in medicine, industry, etc. A key to developing such technologies lies in understanding the fundamental properties of complex electron systems, which are at the heart of this research.

The Chicken and the Egg

On its own, an electron is a fairly straightforward elementary particle, whizzing around the nucleus of an atom in its assigned orbit. But when electrons abandon their solitude and interact with each other to form complex systems, some interesting and unconventional phenomena can result. One example is superconductivity, where electrons -- which by nature repel one another -- group themselves in pairs, allowing current to flow without resistance. Electrons interact by means of their charge, spin (a mechanical property at the heart of magnetism), or lattice (the atomic arrangement, or "cage," of the material in which they're located. Electrons moving through the lattice can cause this cage to deform.)

Mannella wants to unravel these interactions to illuminate the fundamental physical principles behind them. Yet a major hurdle in this type of research has been establishing a cause-effect pattern among the interactions. Does magnetism, for example, render a material metallic, or does a metallic material induce magnetism? This is what Mannella calls a classic "chicken-and-egg" problem, but one he has a plan to help solve using sophisticated experimental tools, including Angle-Resolved Photoemission Spectroscopy (ARPES) -- a technique that observes the distribution of electrons. By taking advantage of ultraviolet laser pulses that last less than a thousand of a billionth of a second, he can excite electrons so rapidly that the interactions between them are destroyed instantaneously. He then monitors the electrons as their interactions begin to re-form, taking note of the timeframe and looking for their respective signatures. The key idea is that, since every interaction has its own characteristic time, one can separate several interactions based on observing how the system goes back to equilibrium after an impulsive excitation.

"Different phenomena have different recovery times," he said. "So if I establish a hierarchy in time of what's going on, I can disentangle the response of the different phenomena."

Mannella explained that his experimental setup uses two laser beams in succession: beam one hits the sample material, followed by a time-delayed beam two -- a pump and probe approach. By delaying the second beam, he said, it's as if you're taking a rapid series of photographs, with each photo corresponding to electronic spectra, or distribution; thus disentangling the electronic interactions.

"So every picture will contain a particular signature which suggests one behavior with respect to another," he said.

He explained that what happens as a function of time delay is very important.

"Suppose that the electrons have a complicated behavior because there are interactions both among the electrons and the electrons interact with the lattice," he said. "Sometimes it is really difficult to disentangle the contributions of the two."

Take, for example, the typical case of vanadium dioxide, a well-known material used in applications such as infrared sensors.

"The experiment would be that one unbinds the electrons from this interaction by basically giving them a 'kick,' and then takes a look at the response of the system," Mannella said. With optical pump-probe measurements it was observed that (the) signature appeared only after a certain time lag. It was an indication that those interactions have to do with the lattice because the lattice is massive and slow to move . . . so you had those signatures but you had to wait a certain time before seeing them, and that was the proof that the lattice is involved. The new twist on these experiments pursued by Mannella's group will be to probe the response of the system following an impulsive excitation by monitoring electrons with Angle Resolved Photoemission, a technique known for its power of observing directly how electrons move in a solid.

Orchestrating Wild Horses

These time-resolved experiments have another key advantage in that they impose coherence on the system. To explain, Mannella pulled up a stop-motion image on his computer showing a bullet flying through four brightly-colored crayons lined up in a row.

This, he explained, is why he uses a pump and probe experimental setup.

"This is a scheme that is used anytime your detector is not fast enough," he said. "Imagine that you have a horse that is running as fast as an electron: you cannot see it. There is no instrument able to see it. So you keep your detector open and imagine that you measure the dark, because this horse is so fast that it's like you see nothing, and then all of a sudden" . . . whoosh -- the horse appears. "So you illuminate your field of view with a flash so you can basically retrieve the motion of the horse as a sequence of pictures that capture its movement, because you can make the flash as fast as you want.

"Now, here's the complication," he continued. "You do not have one horse; you have 10^{23}. If I had only one horse I can use this scheme and determine when the first gallops on the four legs are elevated from the ground. But imagine you have a herd of horses. Your horses are incoherent: what one horse does has no correlation whatsoever with what another one does. So in your picture you see four times 10^{23} because there are four legs. You have to ask, 'What do I want to do to these horses in order to understand something about them?' That's the idea of the pump that imposes the coherence."

The pump, he said, can be thought of as an explosion that startles the horses, causing them to rear; the probe then takes a rapid succession of photographs to see, collectively, when their hooves return to the ground.

Using this kind of research to teach physical principles is a critical aspect of the CAREER grant, and Mannella has worked closely with Physics Professor Marianne Breinig to develop a concrete plan to do just that.

Bridging Gaps and Tweaking Knobs

An expectation of this NSF program is that the scientists involved will become lifetime leaders in integrating research and education. Mannella's proposal incorporates three defined elements to bridge the gap between the lab and classroom: integrating his research into Breinig's sophomore-level Modern Physics course; creating research opportunities for undergraduate students through the department's Summer Fellowship Program; and working with the teaching staff and students of Hardin Valley Academy, a local high school, to develop confidence and competencies in advanced physics principles.

"This is not just about science," Mannella said, adding that outreach and educational components help define an individual as a professor. He said he and Breinig defined a strategy that strives to overcome a significant hurdle in physics education: helping students make sense of concepts when they have no everyday experience to which they can make comparisons.

He explained that in mechanics, for example, there are a number of examples a professor can use, but when it comes to quantum mechanics, "it's difficult for a novice student to refer back to his experience because he doesn't have any. I can refer back to my experience in the lab, but the student cannot." His laboratory, however, can help bridge that gap.

"This is feasible because the kind of lab that we have hosts state-of-the-art instrumentation," Mannella explained. "We have many of the elements that are at the technological front," including powerful lasers and vacuum systems. His research techniques, such as ARPES and low-energy electron diffraction, also blend nicely into the undergraduate physics curriculum.

"These are based on experiments like the photoelectric effect and the Davisson-Germer effect, which the students study and encounter during their first exposure to modern physics," he said. "So if a student studies that an electron is a wave and there is a diffraction pattern, the student can come in my lab and tweak the knob and see that."

While Breinig will explain concepts to students, Mannella will identify activities based on his research that will offer clear, real-life illustrations.

"Imagine a homework problem that would not just be academic -- where you invent a hypothetical situation that you never encounter -- but a problem that can really stem from practical issues that we encounter in the lab," he said.

For example, he has a laser and he needs to find the proper lens to get the appropriate focusa routine necessity in the lab.

"You can show the student that this is important because this is my (laser) light, and I have to go from here to here; I have to focus and I need to buy the proper lens," he explained. "I have a catalog -- what lens do I buy?"

Teaching students the practicalities of research is hardly unchartered territory for him, as his lab has already been a training ground for both university and high school students.

Among those are Emily Finan and Eric Martin, both of whom are undergraduate physics majors. In March 2010, Finan was looking for an opportunity to work in a departmental research lab, and Mannella was among the faculty members who offered to welcome her.

"I liked his mentorship, and I found what they were doing to be the most interesting," Finan said.

In the past year she has worked with Dr. Christine Cheney, a research assistant professor in Mannella's group, and has gained experience with the lab's high-powered laser system and electron-beam evaporator, with plans to work on a new spectrometer system.

Finan said the hands-on aspect has definitely added a new dimension to her physics education.

"There's a really big difference between what you learn in class and what you do day-to-day in the lab," she said, explaining that the two elements "go hand-in-hand. It's reinforced the idea that I want to go into research, in physics in particular."

Martin, who graduated in May, had a similar experience. He began working with Mannella more than two years ago, first doing programming, then moving on to physics research. He has analyzed data from synchrotrons and, with Mannella's support, has travelled to the Advanced Light Source at

Berkeley to take ARPES data. Last fall he worked on X-ray photoelectron spectroscopy experiments using titanium oxide.

"I've learned a tremendous amount about condensed matter, and a lot of additional physics," he explained; including electricity and magnetism, thermal physics, some statistical mechanics, and techniques that utilize the photoelectric effect. "It was really a very full education."

Martin begins a graduate physics program at the University of Colorado this fall and counts his work with Mannella as an advantage in his graduate school applications. He said his research background is comparable to, if not better than, those of students coming from some of the top technical schools in the country.

"That's just from working with Norman," he said. "Without it I would have had no way of standing out. He's a really good physicist and a really good writer. He pushes, but he's relaxed. That really enforces learning. I would advise doing research as a supplement to any physics student's education."

His gift for teaching physics principles with research experience is a cornerstone of Mannella's CAREER grant, as is a philosophy that Finan said he emphasizes both in the classroom and the laboratory: scientific curiosity is more important than purely academic success. He's taught her, she said, that "it's not about making straight A's; it's about looking at things in a new way."

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