PNAS PROFILE

Profile of Jainendra K. Jain

Farooq Ahmed, Science Writer

Theoretical condensed matter physicist Jainendra K. Jain was born and raised in the rural village of Sambhar in the northern Indian state of Rajasthan. Jain recalls that despite the poor educational infrastructure in his school, he fell in love with physics. "The stories of Einstein and Indian physicists Bose and Raman had worked their magic on me," he says. "I used to stay up late at night solving physics problems. I found the beauty of physics in the economy of its explanation."

Jain was elected to the National Academy of Sciences in 2021 and now serves as the Evan Pugh University Professor and Erwin W. Mueller Professor of Physics at Pennsylvania State University, University Park, where he has taught since 1998.

Indian Upbringing

Early in high school, Jain knew he wanted to pursue research in physics but faced opposition from his family. "Because of India's economic circumstances in the 1970s, my father thought I was being foolhardy for not trying to become a doctor or an engineer. But, to his credit, he never forced his opinions on me," Jain says. Jain completed an undergraduate degree in physics at Maharaja College in the Rajasthani capital of Jaipur. He continued with a Master's degree in physics at the Indian Institute of Technology, Kanpur. In 1981 Jain decided to pursue a PhD in the United States at the State University of New York at Stony Brook.

Coming to the United States proved especially transformative for Jain. As a young boy, he had lost a foot in an accident that had left him on crutches. He credits a locally developed experimental prosthesis, now known as the Jaipur Foot, with enabling him to continue his education. Once in the United States, Jain was fitted with an advanced prosthetic that alleviated complications. "This was a turning point in my life, liberating me to focus fully on physics research," he says.

Electron Systems

Although Jain was initially interested in studying high energy physics at Stony Brook, conversations with faculty, including Nobel Laureate C. N. Yang, convinced Jain to switch fields to theoretical condensed matter physics. He began working with Philip Allen, an expert on superconductivity. This decision led to Jain's most prominent scientific contributions. "It happened in many small steps," Jain recalls. Allen set Jain on the task of studying Raman scattering in layered superconductors. He began by calculating Raman line shapes for light scattering from layers of two-dimensional (2D) electron systems. The research was motivated and subsequently verified by the experiments of condensed matter physicist Aron Pinczuk, who was then at AT&T Bell Laboratories.

Jainendra K. Jain. Image Credit: Jennifer Dong (photographer), Penn State Eberly College of Science.

"My thesis work had a profound impact on me because this was my first direct experience that theoretical calculations have a counterpart in reality," says Jain.

Once drawn into two dimensions, further inspiration from Steven Kivelson, then on the faculty at Stony Brook, drove Jain's interest in the fractional quantum Hall effect, one of the seminal discoveries in condensed matter physics.

The Hall effect in three-dimensions, which was discovered in the late 1800s, describes the resistance of a conductor in a magnetic field where the current of electrons flows perpendicular to the direction of an applied electric field. Nearly a century later, the German physicist Klaus von Klitzing observed a phenomenon now called the integer quantum Hall effect. von Klitzing found that in a system of electrons in two dimensions, the Hall resistance, as a function of the magnetic field, changes in a stepwise manner that consists of distinct, flat plateaus: not in a straight slope, as predicted by the original Hall effect. von Klitzing received the 1985 Nobel Prize in physics for the discovery.

"The shocking thing here," says Jain, "was that the values of the Hall resistance on the plateaus are precisely quantized, labeled by integers. These values do not depend on any of the details of the system; they are what's known as a topological invariant. You can take any other 2D electron system, for example graphene, and see precisely the same quantized values of the Hall resistance."

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Theoretically, Jain notes, the integer quantum Hall effect was explained by physicist Robert Laughlin, then at Bell Laboratories, using a model in which electrons do not interact.

Fractional Quantum Hall Effect

Two years after the discovery of the integer quantum Hall effect, in 1982 researchers discovered the one-third fractional quantum Hall effect—a plateau labeled by the fraction one-third—in 2D electron gases that had been subjected to even stronger magnetic fields. The electrons in this state were strongly correlated, they interacted, and oddly enough, they could come together to create excitations with one-third the charge of an electron. Physicists Laughlin, Horst Stormer, and Daniel Tsui received the 1998 Nobel Prize in physics for the discovery and explanation of this fractional effect.

"It seemed in 1983 as though the fractional quantum Hall effect story was complete," says Jain. "But as experimentalists cleaned up their electron samples and kept lowering the temperature, they discovered more and more quantum Hall states labeled by different fractions. These observations motivated influential theoretical works by [Princeton University physicist] Duncan Haldane and [Harvard University physicist] Bertrand Halperin." Close to a hundred fractions have now been found.

After graduating from Stony Brook in 1985, Jain remained intrigued by the fractional quantum Hall effect. Through a postdoctoral fellowship with theoretical condensed matter physicist Sankar Das Sarma at the University of Maryland, he continued thinking about the effect, while actively pursuing other properties of interacting electrons.

"I always found it rather peculiar that even though the fractional quantum Hall effect empirically looked very similar to the integer quantum Hall effect, the fractional effect was so mysterious when the integer quantum Hall effect was relatively straightforward to explain," he says.

Jain recalls that in the winter of 1988, when he was a postdoctoral fellow at Yale University, he had an insight that would set the trajectory of his research career. He could unify the two effects by explaining the fractional effect as the integer quantum Hall effect of a new class of particles that he termed "composite fermions." "Suddenly, everything fit together. I remember telling my wife that I thought I had had an interesting idea, and she still remembers it. But of course, I had no inkling then that it would remain with me for the next 30 years," he says.

Fermions are particles with half-integer spins, such as electrons and quarks. The other category of subatomic particles, such as photons and gluons, have whole-integer spins and are thought of as force-carriers. Composite fermions, which Jain proposed for the fractional quantum Hall effect, consist of electrons bound to two magnetic flux quanta, which can be thought of as quantized constituents of the magnetic field.

Jain quickly worked out and wrote up the details of his composite-fermion hypothesis for the fractional quantum Hall effect and submitted them for publication (1). "I wasn't sure how the community would receive the work," he concedes. A few years later, by the early 1990s, several theoretical and experimental papers confirmed and extended Jain's explanation. The composite fermion formulation revealed the underlying simplicity of the complex phenomenology of the fractional quantum Hall effect and provided the field with clarity.

The existence of composite fermions has many implications. Jain says, "You open a standard textbook on what electrons do and ask whether composite fermions can also do the same. It turns out that yes, they show many of those phenomena, such as forming Fermi seas and crystals, superconductivity, and also much spin-related physics."

Jain was able to further generalize the composite fermion formulation for fractional quantum Hall states by breaking electrons down into hypothetical point particles known as partons, and placing them in integer quantum Hall states (2). Some of Jain's more recent work builds upon this generalization. "Many of the new and delicate fractional Hall states, both theoretically and experimentally, seem to conform to this parton construction," says Jain.

Quantum Phenomena

In 1989 Jain returned to Stony Brook, where he stayed for nearly a decade as a faculty member before joining Pennsylvania State University. He continued to pursue and develop the theory of composite fermions, demonstrating its validity in a variety of contexts and making predictions that could be tested experimentally. In the 1990s computational approaches by Jain and his students enabled work with large systems of composite fermions. This led in subsequent years to detailed comparisons with experiments, including in new materials, such as graphene.

In 2007 Jain published a monograph on the manifestations of composite fermions (3), and, more recently, he penned a chapter for a book he edited with Halperin on the fractional quantum Hall effect (4). The book includes recent research by Jain and collaborators on parton theory and on the Kohn–Sham theory of the fractional quantum Hall effect. Kohn–Sham equations use density functional theory to incorporate interactions between electrons. In materials science, chemistry, or biology, they provide a useful starting point by reducing complexity down to single particles. Jain's work used composite fermions to formulate Kohn–Sham equations for the fractional quantum Hall effect. "A part of our research program has been to develop theoretical methods that can produce reliable results and then use those to explain and predict new phenomena," he explains.

A recent example helped reconcile the experimental observation of spontaneous magnetization of a Fermi sea of composite fermions at low densities. The phenomenon was similar to Bloch ferromagnetism for electrons, in which paramagnetic electrons suddenly align spins and magnetize at low density. Jain and his students provided a theoretical explanation for this finding through a Monte Carlo calculation of composite fermions (5).

Jain's other interests include topological phases, localization, 1D systems, and graphene. Jain's Inaugural Article (6) explores connections with another quantum mechanical phenomenon: superconductivity. Superconductivity in conductive materials occurs when the material's electrical resistance plummets to zero below a certain critical temperature. The article shows that combining the quantum Hall effect with superconductivity can produce topological particles, called skyrmions, in addition to the expected Majorana particles, which are fermions that act as their own antiparticles.

While there are no experimental systems currently able to test the model, Jain remains optimistic about the chances, saying, “I have seen many times in my career that things that seem impossible today become realized many years later in one context or another. My goal is to continue to contribute to good science and collaborate and learn from the younger generation of scientists, whom I find absolutely brilliant.”

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4. J. K. Jain, “Thirty years of composite fermion and beyond” in *Fractional Quantum Hall Effects: New Developments*, B. I. Halperin, J. K. Jain, Eds. (World Scientific, 2020) pp. 1–78.
5. M. S. Hossain *et al.*, Bloch ferromagnetism of composite fermions. *Nat. Phys.* **17**, 48–52 (2021).
6. J. Schirmer *et al.*, Phase diagram of superconductivity in the integer quantum Hall regime. *Proc. Natl. Acad. Sci. USA*, 10.1073/pnas.2208671119 (2022).