From SLUGS to SQUIDS

John Clarke's Remarkable Career in Physics

PHOTO: PEG SKORPINSKY

John Clarke is the world's leading authority on Superconducting QUantum Interference Devices. He joined the Berkeley faculty in 1969, retired in 2010, and now serves as a Professor of the Graduate School.

Berkeley physicist **John Clarke** is enjoying an impressive career in scientific research. Through more than five decades of brilliant work, he has become the world's leading authority on the design, understanding, and application of SQUIDs – Superconducting Quantum Interference Devices. Clarke describes today's SQUIDs as "amazingly diverse, with applications that include physics, chemistry, biology, medicine, materials science, geophysics, cosmology, and quantum information." SQUIDs are iconic examples of the vital contributions physics offers to the well-being of society at large.

Clarke received his PhD from Cambridge University in 1968. While at Cambridge, he met many physicists who visited the Cavendish Laboratory, in particular two young faculty from Berkeley, **Paul Richards** and **Marvin Cohen**. Clarke says that discussions with them inspired him to apply to Berkeley as a postdoc. He came to campus in 1968, joined the faculty the following year, and especially remembers the supportive mentoring of Paul Richards during those early years.

This January, 50 years after his arrival in Berkeley, Clarke presented a colloquium to the Physics Department entitled *The Ubiquitous SQUID: from Cosmology to Medicine*. Cohen introduced the gathering by saying, in part, "John Clarke's approach to physics and education have benefitted from his gift of a clear, uncluttered mind. He has been a great teacher and mentor, and his contributions to science, which range from the properties of matter, to astrophysics, to biomedical physics, were always important advances that pushed these fields forward. In addition to his discoveries, inventions, and other achievements, he has trained people who are world leaders in science."

In his colloquium presentation, Clarke described how he became involved with SQUID technology, how SQUIDs work, how they have evolved, and how they are used today.

THE BIRTH OF THE SLUG

Clarke began his remarks by describing his first months as a graduate student at Cambridge. It was the fall of 1964. His advisor, Brian Pippard, offered him a thesis topic that required measuring voltages of 10^{-12} or 10^{-13} volts, two to three orders of magnitude smaller than the state of the art at the time.

For several weeks, Clarke pondered how to make a better voltmeter. Then a sequence of encounters ensued that would prove pivotal. In November, Brain Josephson, a fellow graduate student of Pippard, gave a talk on Josephson tunneling, a phenomenon he had first predicted only two years earlier and that had just been implemented to demonstrate the first SQUID.

The lecture inspired Pippard to come up with a new idea the very next day – a SQUID-based digital voltmeter that, according to calculations, could achieve a resolution of 10^{-15} volts, far better than what they'd been searching for. Clarke's job was to figure out how to build it.

"I played around for several weeks with bits of niobium wire and foil," Clarke remembered, "coming up with devices that sometimes worked but weren't very reproducible or reliable." One day during afternoon tea – a daily Cambridge tradition – Clarke's lab partner Paul Wraight made a suggestion: "Why don't you freeze a blob of solder on a length of niobium wire?"

"It was a brilliant idea." Clarke noted. "I went back to the lab right away, made it, immersed it in liquid helium in a cryostat – and it worked! All before dinner."

"When I showed the results to Brian Pippard the next morning," Clarke continued, "he was really excited. He unwittingly named the device as soon as he saw it, saying, 'It looks as though a slug crawled through the window overnight and expired on your desk.' All I had to do was to figure out what the acronym SLUG stood for: Superconducting Low-Inductance Undulatory Galvanometer. I used SLUGs in many applications for more than a decade, and it turned out to be an important progenitor of the modern SQUID."

SQUIDS TODAY

"The first practical SQUIDs were primitive by today's standards," Clarke explained. "Today's SQUIDs, fabricated from patterned, multilayer thin films on silicon wafers, offer extraordinary sensitivity to magnetic flux."

In his remarks, he highlighted their impact in a number of applications that exist today only because of the remarkable versatility of the SQUID.

MAGNETIC MEASUREMENT

"By far the biggest selling commercial device that uses SQUID technology," Clarke said, "is made by Quantum Design in San Diego. It's used to measure everything from high-temperature superconductors to blood samples. There are well over a thousand of these systems in use around the world."

GEOPHYSICAL PROSPECTING

Beginning in the late 1970s, Clarke and collaborators used niobium SQUIDs, cooled in liquid helium, for geophysical measurements. Decades later, Cathy Foley and colleagues at the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia developed a system involving high transition temperature SQUIDs, cooled in liquid nitrogen, to search for mineral deposits. So far, Clarke noted, commercial versions of this system have located deposits worth an estimated ten billion dollars, including a two-billion dollar deposit of silver that had been missed by all other techniques.

COSMOLOGY

"SQUIDs are the enabling technology for reading out another superconducting device, the transition edge sensor (TES), used by research groups in cosmology all over the world," Clarke reported.

In particular, detection of the cosmic microwave background (CMB) depends entirely on the TES-SQUID combination. Clarke worked for several years with Physics Department faculty Paul Richards, Bill Holzapfel, and Adrian Lee and their groups to develop a multiplexed readout. Originally, one SQUID was required to read out each of the many sensors required for CMB detection. Clarke invented a scheme by which a single SQUID could read out multiple TESs, ultimately enabling the use of thousands of TESs on a given telescope.

SQUIDs are also the enabling technology in the search for the axion, a candidate particle for the cold dark matter that constitutes 80% of the mass of the universe. If the axion were shown to exist, it would resolve certain discrepancies between the Standard Model of particle physics and experimental observation. Two decades ago, Clarke, Michael Mueck (a member of Clarke's group from Germany) and colleagues developed a SQUID amplifier operating at hundreds of megahertz that, when cooled to a fraction of a degree kelvin, could achieve the quantum limit. "You can't do better than that," Clarke said in a recent press release. "The Axion Dark Matter eXperiment (ADMX), located at the University of Washington, Seattle is a complicated and expensive piece of machinery, and it took a while to build a detector to take advantage of the SQUID sensitivity." In April this year, ADMX achieved the sensitivity required to undertake a meaningful search for the axion.

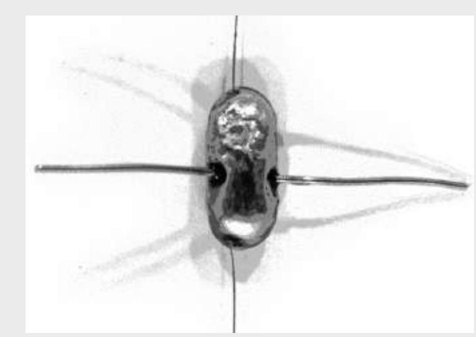
Clarke also noted that low-noise, high frequency SQUID amplifiers have been used to read out quantum bits (qubits) for quantum computing.

MEDICINE – MEG AND ULFMRI

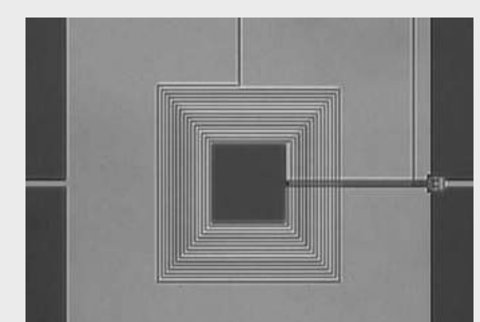
Magnetoencephalography (MEG) systems monitor magnetic signals from the brain for a variety of research and diagnostic purposes, including pre-surgical mapping of brain tumors and monitoring of traumatic brain injury. SQUIDs are an essential component – today's commercial MEG systems typically contain more than 300 SQUIDs.

One of the most intriguing potential applications for SQUIDs is ultra-low frequency magnetic resonance imaging (ULFMRI), developed with the late Berkeley physicist **Erwin Hahn**, Berkeley chemist **Alex Pines**, and other collaborators. "A significant advantage of ULFMRI is that it offers much better contrast between certain types of tissue than conventional, high field MRI," Clarke explained. "For example, ULFMRI clearly resolved prostate cancer and normal tissue in ex vivo specimens. Clarke reported that he, in collaboration with **Ben Inglis** in Berkeley's Brain Imaging Center, and other groups around the world are making substantial progress toward new-generation ULFMRI systems that are likely to achieve significant improvements in spatial resolution in the next couple of years.

A webcast of the colloquium can be viewed online at physics.berkeley.edu.



The SLUG – a precursor of today's SQUIDs – was first built by John Clarke while he was a graduate student at Cambridge University. One of his SLUGs now resides in the museum of Cambridge's Cavendish Laboratory.



Today's SQUIDs are fabricated using a wafer scale process and photolithography.