SQUIDs: Then and Now

- SQUIDs: Then
- SQUIDs: Now
- The diversity of SQUIDs
  - Ultralow field magnetic resonance imaging
  - Cold dark matter: The hunt for the axion

History Day
Superconductivity Centennial Conference
Den Haag
The Netherlands
September 21, 2011

Support:
DOE Basic Energy Sciences
DOE High Energy Physics
National Institutes of Health
BBN Technologies
SQUIDs Then
Brian Josephson Explains Tunneling

Courtesy Brian Josephson
Flux Quantization

\[ \Phi = n \Phi_0 \]

\[ \Phi_0 \equiv \frac{h}{2e} \approx 2 \times 10^{-15} \text{Tm}^2 \]

is the flux quantum

Half-centennial!

Vibrating s/c tube in a coil

Deaver and Fairbank 1961

Torque on a s/c tube

Doll and Näbauer 1961
Josephson Tunneling

Josephson 1962
Half-Centennial Next Year!

Anderson and Rowell 1963

I = I₀ sin δ
δ = φ₁ − φ₂
dδ/dt = 2eV/ℏ
= 2πV/Φ₀

Sn-SnOx-Pb
1.5 K

0.006 G
0.4 G

V

CURRENT IN mA

VOLTAGE IN mV

I → Superconductor 1 → Insulating barrier → Superconductor 2 → I

~ 20 Å
Birth of the Superconducting Quantum Interference Device (SQUID)

- Critical current versus applied magnetic field for two different junction spacings
- Rapid oscillations due to interference, slow oscillations due to diffraction
- Essential physics analogous to two-slit interference in optics

Jaklevic, Lambe, Silver and Mercereau 1964
Autumn 1964: Brian suggests that a SQUID would make an exquisitely sensitive voltmeter
The SLUG
(Superconducting Low-Inductance Undulatory Galvanometer)

Nb wire
and solder

Niobium

I

I

Copper

SnPb solder

5 mm

I

Voltage

Current $I_B$ in niobium wire

JC February 1965
The SLUG as a Voltmeter

Voltage noise
10 fVHz$^{-1/2}$
John Wires up a SLUG

Courtesy Gordon Donaldson
Other SQUID Designs

Niobium structures

Zimmerman and Silver 1966
Adjustable Niobium SQUID

Nb wire and foil

0.03” Nb wire

0.001” Nb foil

0.001” mylar

Beasley and Webb 1967
Thin-Film Cylindrical SQUID

- Nb-NbOx-PbIn junctions
- Shadow masks

$10^{-14} \text{ tesla Hz}^{-1/2}$ (10 fTHz$^{-1/2}$)

Goubau, Ketchen, JC 1974
SQUIDs Now
Nb-AlOx-Nb Tunnel Junctions

Trilayer process

• Deposit Nb film as base electrode
• Deposit Al film
• Grow AlOx layer thermally in O₂
• Deposit Nb film as counter electrode

Standard process for all low-\(T_{c}\) electronics

Rowell et al. 1981
Thin-Film, Square Washer DC SQUID

- Wafer scale process
- Photolithographic patterning

SQUID with input coil

Josephson junctions

Ketchen, Jaycox (1981)
Flux Noise in the SQUID

White noise
\(2 \times 10^{-6} \, \Phi_0 \, \text{Hz}^{-1/2}\)
Superconducting Flux Transformer: Magnetometer

Closed superconducting circuit

Magnetic field noise
\( \sim 10^{-15} \text{ THz}^{-1/2} \)

SQUID

Room temperature electronics
Magnetic Fields

- **1 tesla**: Conventional MRI
- **10^-2 tesla**: Earth’s field
- **10^-4 tesla**: Urban noise
- **10^-6 tesla**: Car at 50 m
- **10^-8 tesla**: Human heart
- **10^-10 tesla**: Fetal heart
- **10^-12 tesla**: Human brain response
- **10^-14 tesla**: SQUID magnetometer

1 femtotesla = 10^-16 tesla
The Diversity of SQUIDs
Quantum Design "Evercool"

Cut-away Dewar View

- Coldhead controlled by remote compressor
- First stage cools the shield to 40 K
- Second stage cools the condenser to 4 K
- Condenser unit liquefies the helium gas
High-$T_c$ SQUIDs Prospecting for Mineral Deposits

![Image of SQUID equipment in a rocky environment]

Courtesy Cathy Foley, CSIRO
Gravity Probe-B
Tests of General Relativity

- Geodetic effect—curved space-time due to the presence of the Earth
- Lense-Thirring effect—dragging of the local space-time frame due to rotation

Courtesy Stanford University and NASA
MiniGRAIL: Gravitational Wave Antenna
Leiden University

- Spherical gravitational wave detector
- Temperature: 20 mK
- Diameter: 650 mm
- Resonance frequency: 3160 Hz
- Motion coupled to a transducer that amplifies the motion, and couples flux into a dc SQUID
- Quantum limited strain sensitivity: $\frac{dL}{L} \sim 4 \times 10^{-21}$
SPT: South Pole Telescope

- Antarctica 9,500 feet
- 10 meter dish
- 960 Transition Edges Sensors with multiplexed SQUID readout
- SPT will survey 4,000 square degrees of sky in the next two years, and is expected to find large numbers of galaxy clusters.

The Bullet Cluster
CardioMag Imaging System for Magnetocardiography
300-Channel SQUID Systems for Magnetoencephalography (MEG)
Ultralow Field
Magnetic Resonance Imaging
High-Field Magnetic Resonance Imaging

- Magnetic field $B_0 = 1.5$ T
- Proton NMR frequency $\nu_0 \approx 64$ MHz
- What if we were to lower the magnetic field and NMR frequency by a factor of $10^4$?

Courtesy GE, Inc.
ULF MRI Coil Geometry

- \( B_x \) compensation coil
- Low noise cryostat containing SQUID
- Gradient coils
- \( B_0 \) coil (measurement field)
- \( B_1 \) coil (excitation field)
- \( B_p \) coil (prepolarization field)

- Gradient fields define voxels in space in the same way as in high-field MRI

- \( B_0 = 132 \ \mu T \)
- \( \nu_0 = 5600 \ \text{Hz} \)
Three-Dimensional *In Vivo* Images of the Arm
**T$_1$-Weighted Contrast Imaging**

- If two different types of tissue have the same proton density, a conventional MRI pulse sequence may not distinguish them.

- T$_1$ depends strongly on the environment, and can be used to differentiate tissues types using a T$_1$-contrast pulse sequence.

- T$_1$ contrast can be much higher in low fields than in high fields.
Measurements on *Ex Vivo* Prostate Tissue

- Malignant prostate removed surgically at UCSF hospital.
- Pathologist cuts two small tissue samples, one healthy and one cancerous (Blind: we do not know which is which).
- Samples rushed to Berkeley in a biohazard bag placed on ice.
- $T_1s$ measured: $T_{1A} > T_{1B}$
- Specimens are returned to UCSF where the pathologist characterizes a thin slice of each specimen.
Contrast \((T_{1A} - T_{1B})/T_{1A}\) vs. \% Difference in Tumor Content for each Specimen Pair

\[
\delta = \frac{T_{1A} - T_{1B}}{T_{1A}}
\]

- \(T_{1}(100\% \text{ normal}) = (1.43 \pm 0.10) \ T_{1}(100\% \text{ tumor})\)

- Sufficient for \textit{in vivo} \(T_{1}\)-weighted contrast imaging
$T_1$-Map of Prostate Slice

- Dark lines indicate histology, which is performed on a thin slice.
- $T_1$ map is averaged over the entire thickness.
- Map clearly shows $T_1$ contrast

- Tissue identified through histological mapping
- Tissue is *healthy* unless labeled otherwise
- $X + Y$: Gleason score of tumors; 5 is the most advanced
- BPH: Benign Prostatic Hyperplasia
- GPS: Gland Poor Stroma
Outlook

- Microtesla MRI has the advantage of significantly higher $T_1$ contrast than high-field MRI.

- Other kinds of cancer: Do other types of tumors show $T_1$ contrast similar to that of prostate tumors?

- New funding to study *ex vivo* breast cancer

- National Institutes of Health provided funding to build a prototype system for *in vivo* imaging of prostate cancer.

- Next step: *in vivo* imaging
Cold Dark Matter:
The Hunt for the Axion
## Cosmic Microwave Background: “The Cosmic Rosetta Stone”

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrinos</td>
<td>0.6%</td>
</tr>
<tr>
<td>Baryons (ordinary matter)</td>
<td>4.6%</td>
</tr>
<tr>
<td>Dark Energy (DE)</td>
<td>73%</td>
</tr>
<tr>
<td>Cold Dark Matter (CDM)</td>
<td>22%</td>
</tr>
</tbody>
</table>

• Thus 95% of the universe is unknown!
Cold Dark Matter

A candidate particle is the axion, proposed in 1978 to explain the absence of a measurable electric dipole moment on the neutron

Predicted mass:

\[ m_a \approx 1 \, \mu\text{eV} - 1 \, \text{meV} \ (0.24 - 240 \, \text{GHz}) \]
Resonant Conversion of Axions into Photons

Pierre Sikivie (1983)

Primakoff Conversion

HEMT* Amplifier

Magnet

Cavity

Expected Signal

$\frac{\Delta \nu}{\nu} \sim 10^{-6}$

*High Electron Mobility Transistor

Need to scan frequency
Axion Detector at Lawrence Livermore National Laboratory

- Cooled to 1.5K
- 7 tesla magnet

Scan Time

Using a HEMT amplifier, time to scan the frequency range from 0.24 to 0.48 GHz: 270 years
In the classical limit theory predicts $T_N \propto T$.

In the quantum limit: $T_{QL} = hf/k_B$.

Closest approach to quantum limit:

At 799 MHz:
$T_N = 47 \pm 5$ mK
$T_{QL} = 38$ mK

HEMT $T_N \approx 2$ K
Scan Time

• Using a HEMT amplifier, time to scan the frequency range from 0.24 to 0.48 GHz ≈ 270 years.

• The HEMT has been replaced with a SQUID amplifier. With the system cooled to 50 mK with a dilution refrigerator, time to scan the frequency range from 0.24 to 0.48 GHz ≈ 100 days.

• A SQUID amplifier was successfully operated on the axion detector at 1.5 K to demonstrate proof-of-principle.

• Given the success of this trial run, the Department of Energy has funded the installation of a dilution refrigerator to cool the cavity and SQUID to 50 mK. This will enable an effective search for the axion over the energy range 1 – 10 µeV.
Epilogue

• SQUIDs are amazingly diverse, with applications in physics, chemistry, biology, medicine, materials science, geophysics, cosmology, quantum information,........
• SQUIDs are remarkably broadband: \(10^{-4}\) Hz (geophysics) to \(10^9\) Hz (axion detectors).
• The resolution of SQUID amplifiers is essentially limited by Heisenberg’s Uncertainty Principle.
• Microtesla MRI, the axion search, and a host of other applications, exist only because of the extraordinarily low noise of the SQUID—which in itself seems to be a very tiny part of the whole system.
Thank You!

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