Superconducting niobium nanotip electron field emitter

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Motivation: New cold electron field emitter for microscopy and QIS

General motivation:
Using electron quantum features such as
- Superconductivity
- Coherence
- Entanglement

For:
- Microscopy/Spectroscopy
- Quantum communication
- Sensor applications

Specific motivations:
1) Development of a coherent, intensive electron source with ultra-low energy distribution (SBIR with Electron Optica)
2) Development of an entangled two-electron field emitter (DOE QIS project “QUINTESSENCE”)

In analogy to quantum information science (QIS) with entangled two-photon source

Will allow unique tools:
⇒ Ultra-low energy distribution electron beams
⇒ Decreasing aberration effects in microscopy
⇒ Ultra-high resolution electron spectroscopy
⇒ QIS with entangled electrons
⇒ Non-interactive soft surface analysis
⇒ Two-electron interferometry
⇒ Decoherence studies for quantum materials
Introduction: Electron beam emitter types

Thermal emission:

Heating a metallic cathode:

⇒ Population in the electron density of states above the Fermi energy $E_F$
⇒ According to the Fermi-Dirac distribution
⇒ Electrons above the work function $W$ are emitted into vacuum
⇒ Thermionic emission
⇒ Broad energy distribution
Cold field emission:

- Lowering Coulomb barrier by field voltage
- Enables tunneling Fermi energy $E_F$
- Described by Fowler-Nordheim distribution
- Narrow energy distribution

Fowler-Nordheim field emission:

Field enhanced by tip geometry

$$F = \beta V$$
Resonant tunneling field emission

⇒ High aspect ratio nanoprotrusion on a nanotip
⇒ Discrete localized surface states supplied by bulk Fermi sea electrons
⇒ Allows ultra-narrow energy distribution when state is close to $E_F$

Total energy distribution

$$g(E, T) = g_{FE}(E, T) \sum_j g_j(E, T)$$

Energy distribution from tip field emission

Local density of states for each discrete state (surface energy bands)

Additional due to geometry:
⇒ Field enhancement and self-focusing: low emission angle
Field emitter test and characterization vacuum setup established in the Quantum Lab 1201 at the Berkeley Lab Molecular Foundry:

Our approach:
⇒ Fabricate monocrystalline superconducting Nb nanotip
⇒ Measuring electron energy spectrum in analyzer
⇒ Determining pair-correlations with delay line detector
Nb nanotip emission at 4K: Observation of surface states with ultralow energy distribution

- At tip voltage of -650 V best full-width-half-maximum (FWHM) value: 19 meV
- Subtracting instrument noise/resolution: FWHM = 16 meV
- About one order of magnitude lower than conventional cold field emitter!

Related to annealing process:
- 3 classes of field emission observed

Unpublished data, visible in the live presentation
Nb nanotip at 4K: field emission characterization

Unpublished data, visible in the live presentation
Do we really have surface band structures?

Can be checked by changing the local field on the tip:
⇒ Applied -604 V on tip: Measured peak $E_1$
⇒ Applied extractor lens voltage of +170 V
⇒ Emitted current went up (to 1 nA) and peak shifts down to $E_2$
⇒ Both distributions visible: Fowler-Nordheim and surface state
⇒ Comparable to data in literature

Data comparison:
¬ W-tip surface band structure field emission by Binh et al.:

V.T. Binh et al., PRL 69, 2527 (1992)

Unpublished data, visible in the live presentation
Correlated 2-Electron field emission from Nb tip in superconducting state possible?

- Idea based on experiment by Nagaoka et al. with Nb tip cooled well below $T_c$ (9.2 K)
  - 10-fold increase in intensity (rel. to 25 K)
  - 10-fold smaller energy distribution
  - Claim to be a BCS quantum effect
- Theory suggest (Yuasa et al.): pairwise, entangled emission
- Solid state measurements and Josephson junctions support that assumption

Our observation:

- Energy spectra did not change around $T_c$
- We made rigorous correlation measurements with delay line detector
- However, no evidence found for correlated electron pairs yet!

Possible reason for missing two-electron emission: The Nottingham effect

Emitted electrons locally heat the tip:

- The Nottingham effect is characterized by the average energy difference from Fermi energy of the emitted electrons.
- Since at low temp. most electrons are below $E_F$: local heating of electron exit region.
- Assumption: Local tip heating above $T_c$.

![Graph showing the energy levels and emissions](image)

**Figure 1:**
- **Vacuum**
- **Thermionic emission**
- **Nottingham cooling**
- **Field emission**
- **Nottingham heating**
- **Schottky-Nordheim barrier**

**Graph Data:**
- Protrusion Tip
  - $I_{PE} \sim 9 \times 10^{-12} \text{ A}$
  - $I_{PE} \sim 3 \times 10^{-13} \text{ A}$

**Figure 2:**
- $\Delta T (K)$ vs. $V_{App}(\text{V})$

*Taken from lecture by V. Zadin, University of Tartu*

*V.T. Binh et al., Surface Science Letters 279 L197 (1992)*
Path to overcome Nottingham heating: Nottingham cooling!

Shown in literature for tungsten with nano-protrusion:

⇒ Peaks from the surface band structure can move above $E_F$ at low voltages
⇒ Nottingham heating turns to Nottingham cooling!
⇒ However, only few electrons left at 4K above $E_F$

Shifting peak position with voltage (for tungsten):

Possible way to cool the tip by emission and get correlated e-pairs:

⇒ High nano-protrusions on sharp tip
⇒ Low voltage
⇒ Low emission current

Probably helpful: Superconducting electron pairs at $E_F$
Summary

- Development of coherent superconducting electron field emitters for QIS and microscopy
- Realized a field emitter measurement and characterization setup and fabricated a monocrystalline Nb nanotip
- Observed Nb surface state field emission at 4K with extremely narrow energy distribution FWHM of 16 meV
- Stable, bright emission in ~6 deg. angle
- Increasing beam current with xenon gas coverage by two orders of magnitude
- Efforts towards entangled two-electron beam source, currently limited assumable by Nottingham heating
- Proposed solution: pushing surface states beyond \( E_F \) to initiate Nottingham cooling
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Thank you for your attention!

The End