Quantum Effects
Conductance, Quantum dots & Superconductivity

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Introduction

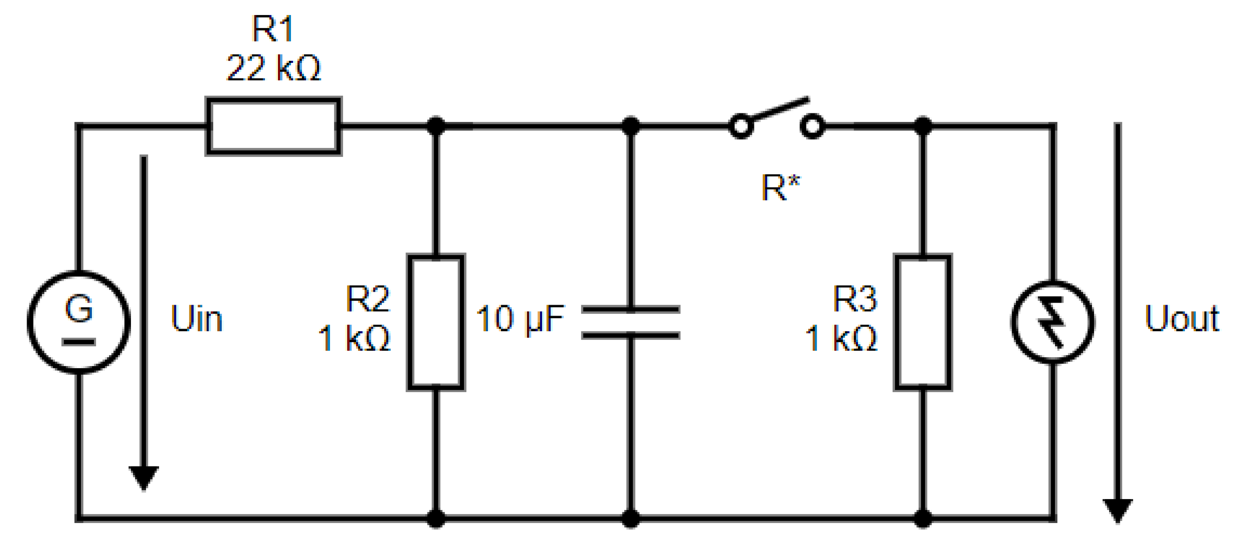
This work aims to demonstrate quantum effects through three experiments. First, quantum electrical conduction in one dimension is studied. Indeed, the quantization of the conductance in a point contact interrupter was demonstrated. Then, light emission and absorption spectra of quantum dots in CdSe nanocrystals were recorded. Characteristic physical quantities such as the relaxation time and the size of the quantum dots were computed. These have various applications one of which are low-threshold lasers[1]. Finally, superconductivity was analyzed in a sensitive magnetometer based on Josephson effect: the SQUID. Its extreme sensitivity makes it ideal for studies in biology. Magnetoencephalography, for instance, exploits that feature to make inferences about neural activity inside brains[2].

Quantum Conductance

Theory:

1D quantum conductance → Landauer-Büttiker formalism (ballistic electrons, no collisions) [3]

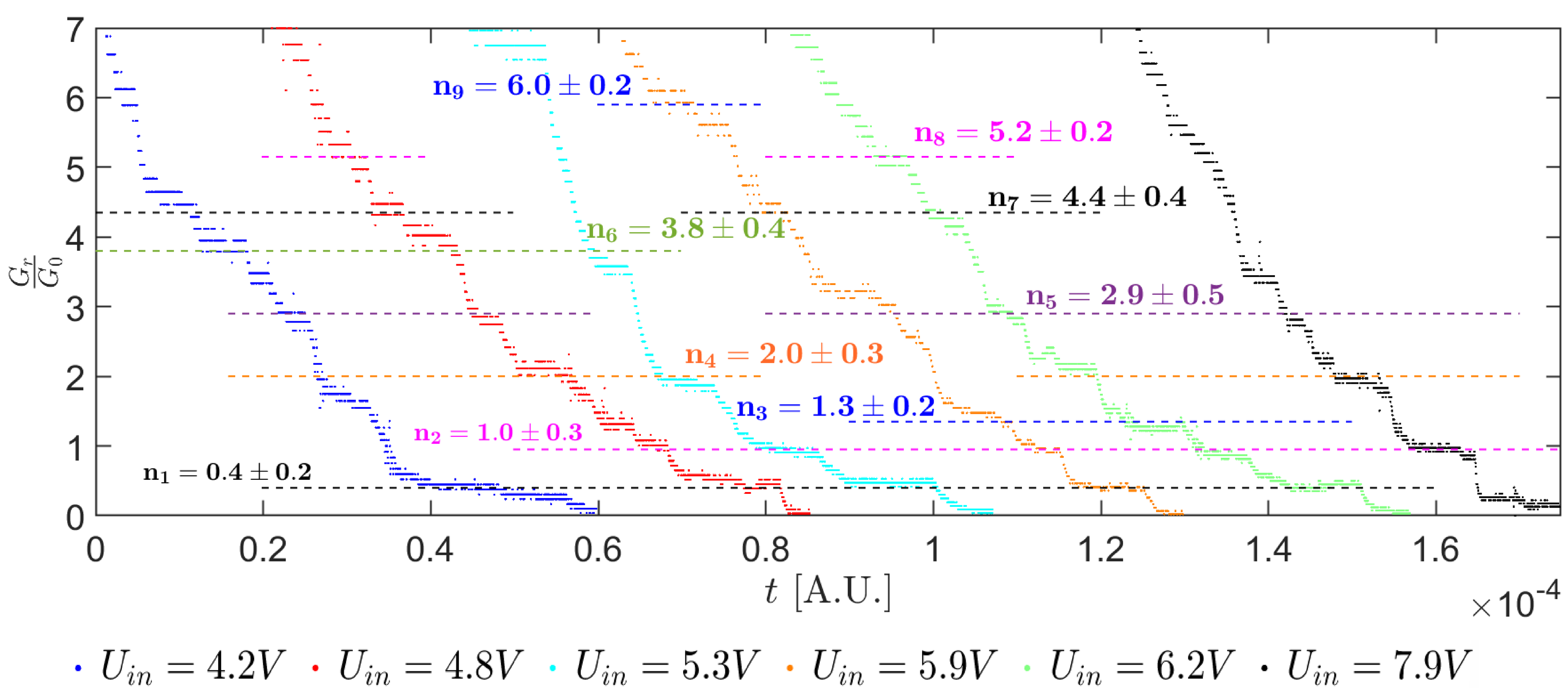
$$G_n = \frac{2e^2}{h} n = G_0 n \quad \text{with } G_0 = 7.75 \cdot 10^{-5} \Omega^{-1}$$



$$G^* = \frac{1}{R^*} = \frac{R_1 + R_2}{R_2 R_3 \left(\frac{U_{in}}{U_{out}} - 1\right) - R_1(R_2 + R_3)}$$

Evidence of Quantum Conductance:

- **9 levels** identified
- At lower values of n, the levels appear **more frequently** (e.g. $n = 6$ appear only once) → Classical limit is attained
- Some values of n are **not integer** → not expected



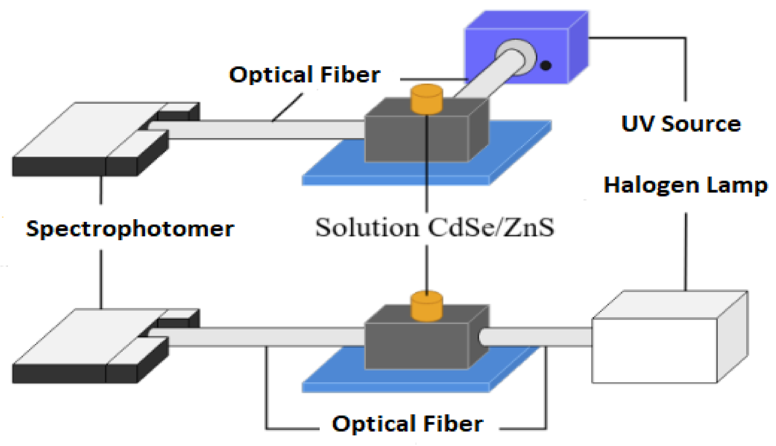
Quantum dots in CdSe nanocrystals

Theory:

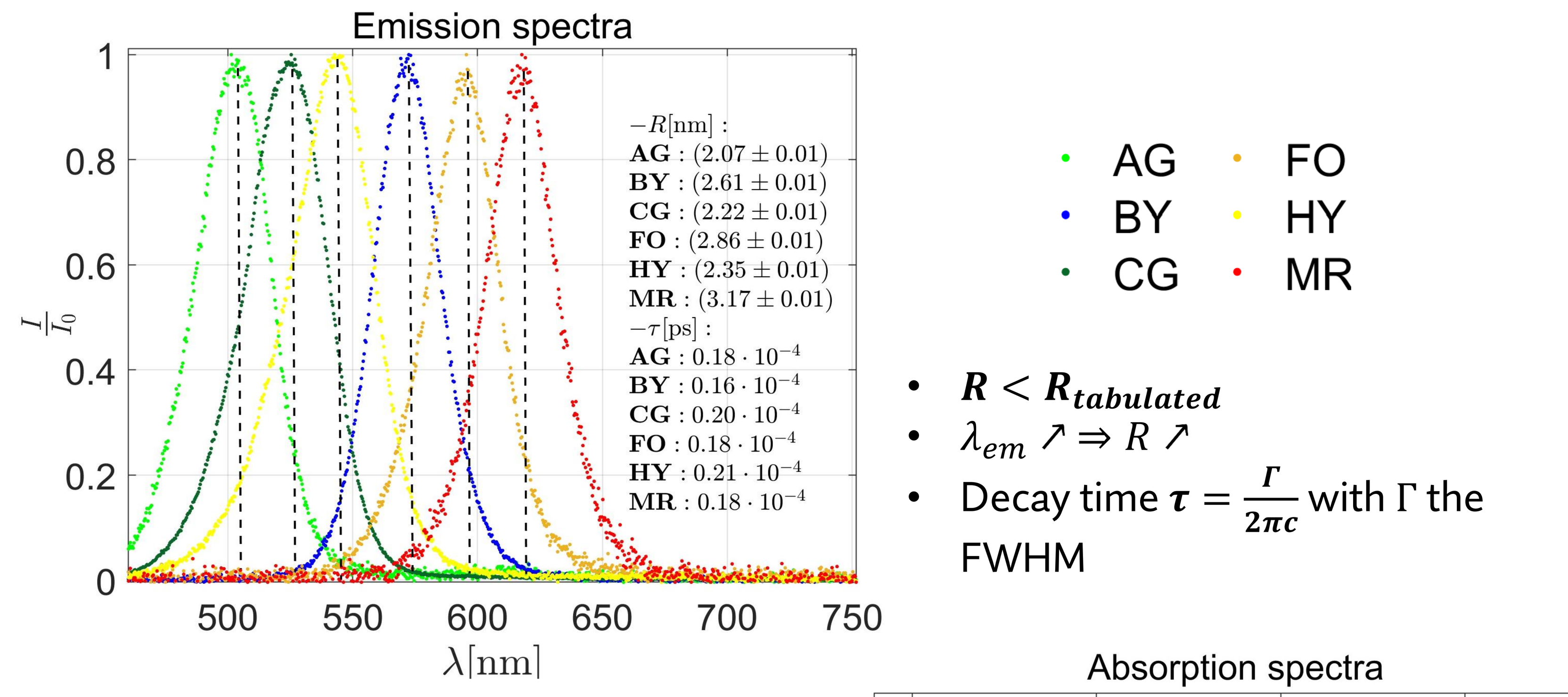
- **Quantum dots (QDs)** = semiconductor nanocrystals behaving as a potential well. Their size → quantum confinement properties
- If a crystal has a microscopic size R → free electrons and holes behave like **quantum particles** in a potential well.
- **Excitation energy** at 1st level for CdSe crystal:

$$E \approx E_g + \frac{h^2}{8R^2}\left(\frac{1}{m_e} + \frac{1}{m_h}\right) - \frac{1.8e^2}{4\pi\varepsilon_{CdSe}\varepsilon_0 R}$$

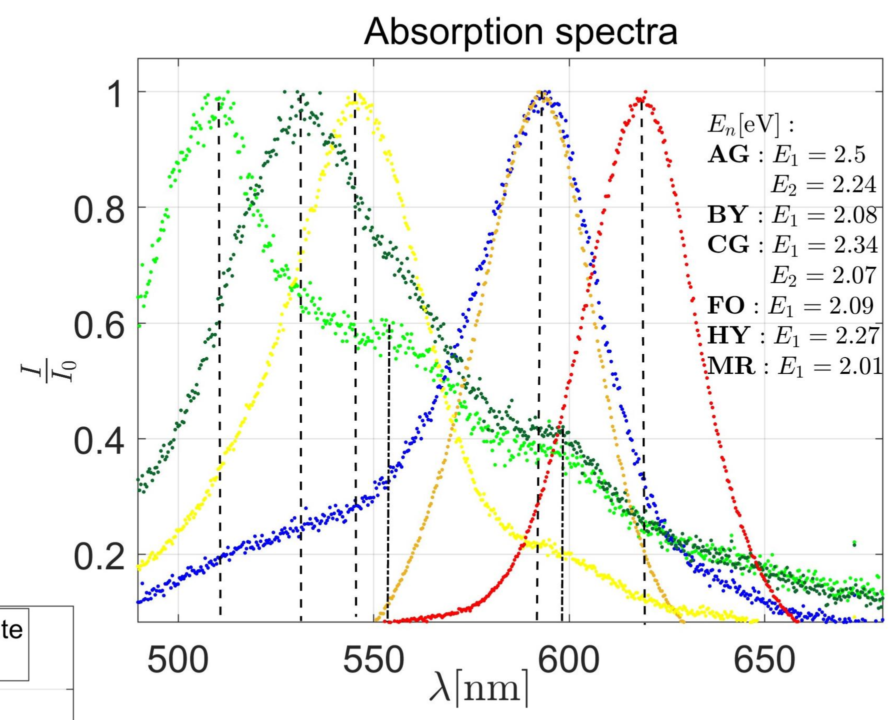
E_{gap}= 1.72eV, $m_e = 0.13 m_0$ and $m_h = 0.45 m_0$, $\varepsilon_{CdSe} = 10$ F/m



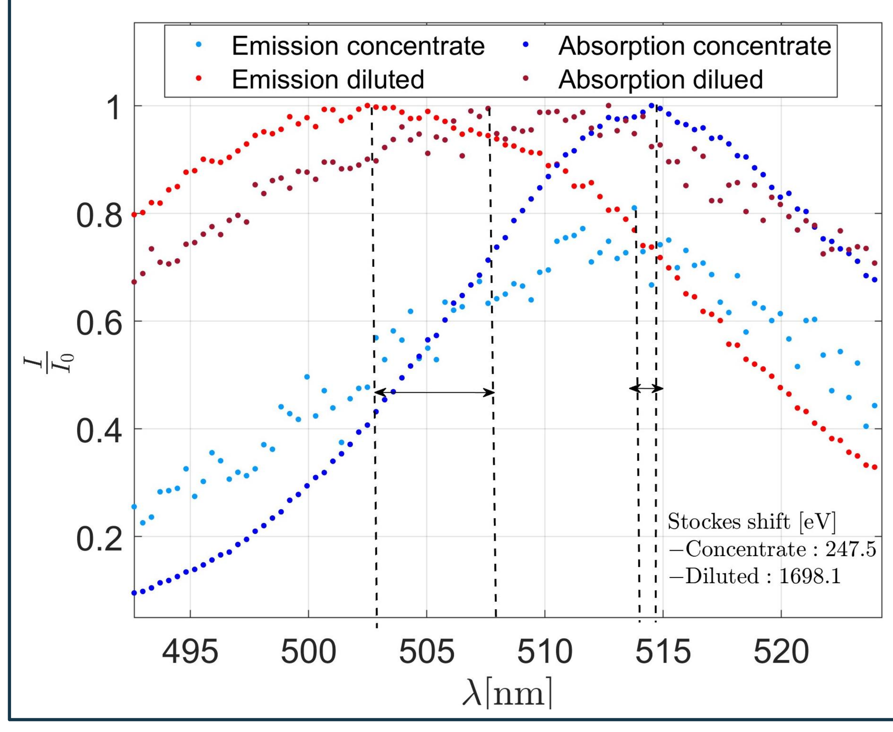
Evidence of Quantum Dots :



- $R < R_{tabulated}$
- $\lambda_{em} \nearrow \Rightarrow R \nearrow$
- Decay time $\tau = \frac{\Gamma}{2\pi c}$ with Γ the FWHM

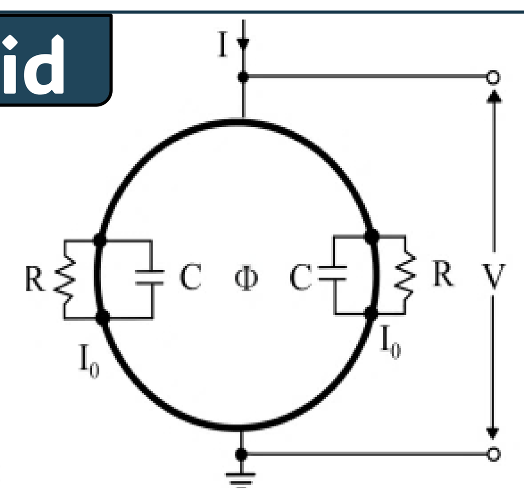


- The peak corresponding to the longest wavelength is the first absorption/excitation peak
- λ_{abs} close to $\lambda_{abs,tabulated}$



- Stockes shift: $\lambda_{em} > \lambda_{abs}$
- Stockes shift changes with the concentration → not expected
- concentration $\nearrow \Rightarrow \lambda_{abs} \nearrow$

Squid

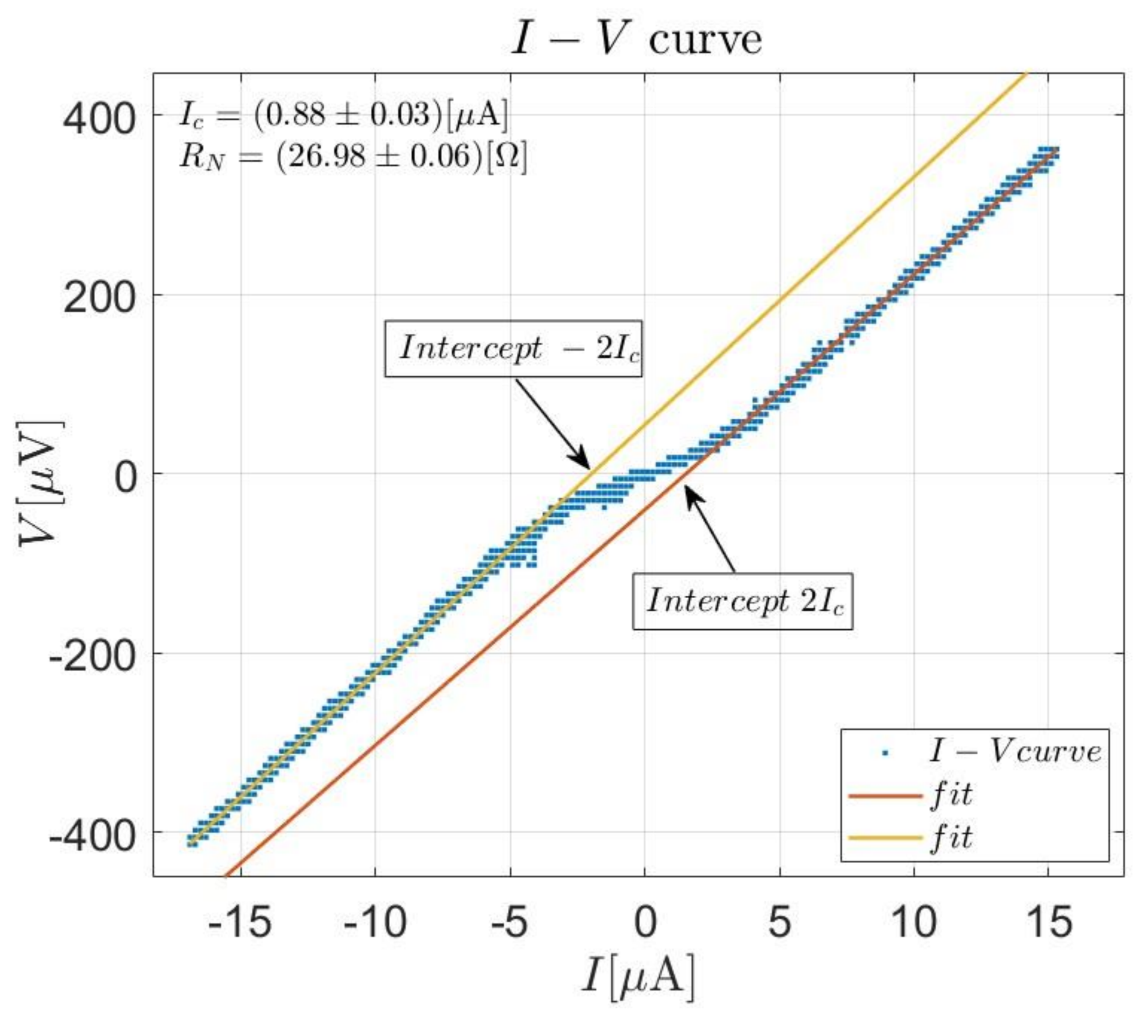


Theory:

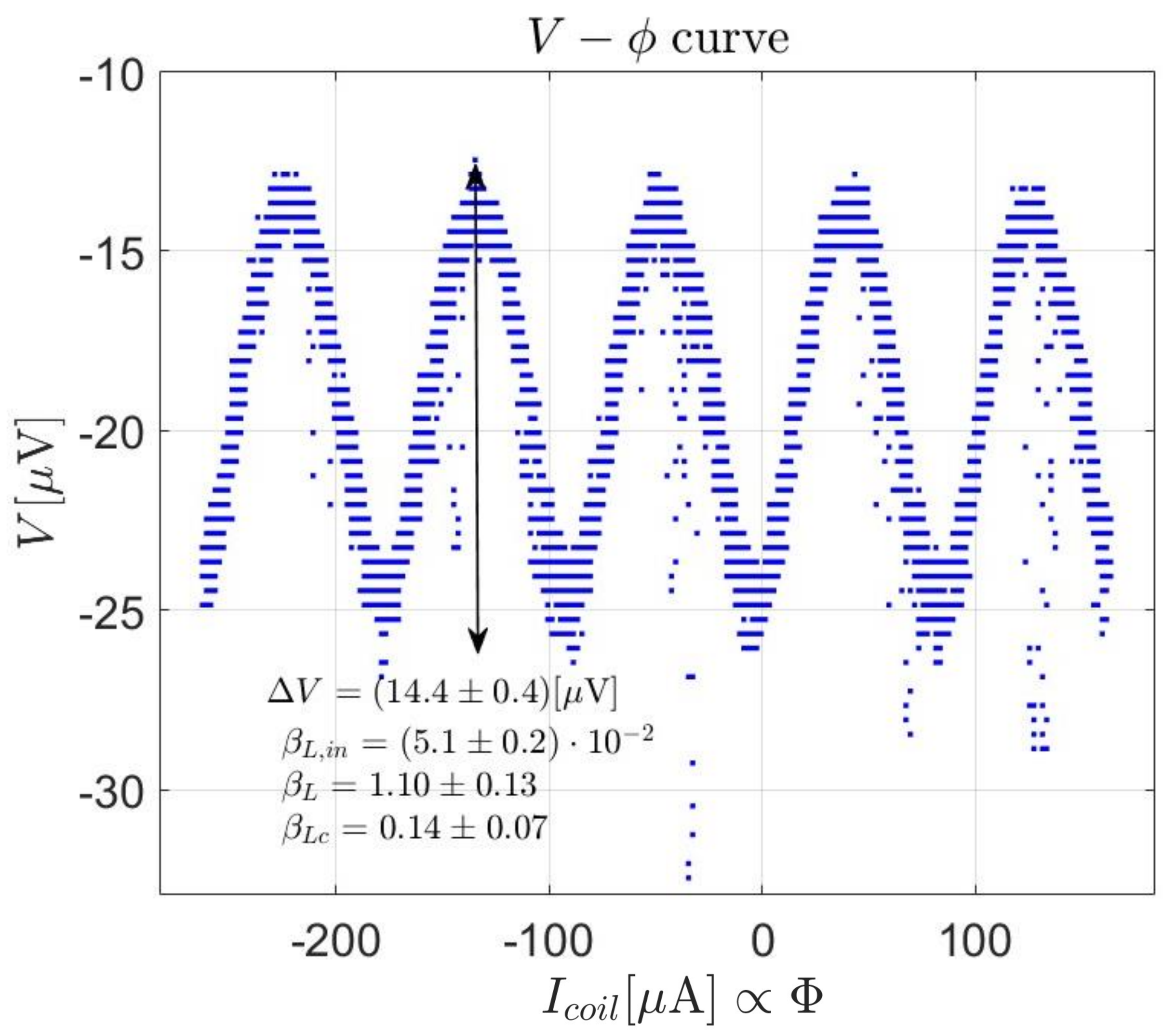
- SQUID → sensitive magnetic detector.
- Two Josephson Junctions (JJ) in **parallel** on a closed **superconducting loop**
- Electrons can tunnel through the insulator → **Josephson Effect** → quantum phase shift.
- Total magnetic flux through the loop is an **integer** multiple of the flux quantum $\phi_0 = h/2e$ [4]
- Modulation parameter:
- $\beta_{L,in} = \frac{2I_c L}{\phi_0}$ (inducive)
- $\beta_L = \frac{4 I_c R_N}{\pi \Delta V} - 1$ (T neglected)
- $\beta_{Lc} = \frac{2I_c L}{\phi_0} = \frac{4 I_c R_N}{\pi \Delta V}\left(1 - 3.57\frac{\sqrt{k_B T L}}{\phi_0}\right) - 1$ (corrected)
- A coil generates an external magnetic flux through the SQUID

Evidence of Superconductivity:

- $T = 77$ K and $L = 73$ pH inductance of the SQUID loop[5]
- When $I \approx 0$A (plateau) , JJ has **no resistance** → superconducting
- I_c : **10 times lower** than predicted by manufacturer[5]



- **Periodic** relationship between the voltage V and the applied magnetic flux ϕ
- ΔV → within **expected** range i.e. between $10\mu V$ and $30\mu V$



Conclusion

The experiment successfully demonstrated three quantum effects. Conductance levels were quantified in a point contact interrupter. The study of fluorescent nanocrystals of CdSe/ZnS showed the quantum confinement effect. Superconductivity and magnetic flux quantization were also observed in the SQUID through different characteristic curves. However, the critical current and the quality factors found empirically differed consequently from the tabulated values.

References

[1] D. Porotnikov, B. Diroll, D. Harankahage, L. Obloy, M. Yang, J. Cassidy, C. Ellison, E. Miller, S. Rogers, A. Tarnovsky, R. Schaller, and M. Zamkov. "Low-threshold laser medium utilizing semiconductor nanoshell quantum dots." *Nanoscale* 12, no. 33 (2020).
[2] R. Hari and R. Salmelin. "Magnetoencephalography: From SQUIDs to neuroscience." *NeuroImage* 61, no. 2 (June 2012): 386-396.
[3] P. Jacquod, "Solid State Physics II - The Theory of Quantum Transport." Lecture notes, EPFL (2015).
[4] Schmelz, M., & Stolz, R. (2017). Superconducting Quantum Interference Device (SQUID) Magnetometers. In A. Grosz, M. Haji-Sheikh, & S. Mukhopadhyay (Eds.), *High Sensitivity Magnetometers* (Smart Sensors, Measurement and Instrumentation, Vol. 19). Springer.
[5] STAR Cryoelectronics, CLL, Mr.SQUID User's Guide