John Clem—Theoretical Guide to Experimentalists

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John Richard Clem 1938–2013

John Richard Clem was born on 24 April 1938 in Waukegan, Illinois, USA, into a family of schoolteachers. Supported by scholarships to the University of Illinois at Urbana-Champaign, he obtained his BS in 1960 and his MS in 1962, both in engineering physics. In 1965, he earned his PhD under John Bardeen with his thesis entitled “Effects of anisotropy of the superconducting energy gap”. From then on, he continued to perform theoretical research in the field which can be summarized as “phenomenology of superconductors”, and which became his lifelong research subject.

After postdoctoral appointments at the University of Maryland and the Technical University of Munich, in 1967, John joined the Iowa State University Department of Physics and Astronomy and the Ames Laboratory. There he worked for 46 years in the broad field of type-II supercon-

ductivity, closely collaborating with many colleagues. On 2 August 2013, he passed away in Ames, Iowa, USA, after a 4-year battle with mesothelioma.

I met John for the first time in 1968 at the 11th International Conference on Low Temperature Physics in St. Andrews, Scotland. Our encounter resulted in our long and intensive collaboration, mostly on the subject of the static and dynamic properties of magnetic flux structures in superconductors. Soon after St. Andrews, I arranged that John was hired as a theoretical consultant in the Solid State Science Division of Argonne National Laboratory, where I was working at the time.

In this brief memorial lecture, I concentrate on a few examples of my collaboration with John, covering mainly the first half of John’s career. His activities during the second half, in particular dealing with high-temperature superconductivity, are likely to be discussed by others.

In the late 1960s, at Argonne, we started magneto-optical experiments studying the intermediate state of type-I superconductors. One of the subjects dealt with the entry of magnetic flux into the superconductor and the entry magnetic field H^* [1]. If, in addition to an applied magnetic field, an electric transport current is applied to the superconductor, it was shown theoretically that the entry field H^* decreases linearly with the transport current, in good agreement with the experiments. Further, the Gibbs free-energy barrier against irreversible magnetic flux entry into a superconductor was studied experimentally and theoretically [2].

Our collaboration at Argonne culminated with the two of us organizing the International Conference on Magnetic Structures in Superconductors, 5–8 September 1973 at Argonne, attracting about 100 people, including people from Canada, Europe, Japan, and South America. Subsequent to the conference, we published a conference summary [3].

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Another subject dealt with the dynamics of magnetic flux structures in superconductors. We investigated the motion of magnetic flux tubes in type-I superconductors at 100 ns time resolution, using a stroboscopic magneto-optical observation technique [4]. Furthermore, the time-dependent voltage generated by flux motion across a superconducting strip was calculated in the case of single-quantum vortices or multi-quanta flux tubes [5]. The theory was then applied to obtain the exact shape of the voltage pulses expected from different measuring circuits attached to a superconducting strip. Another paper dealt with the distribution of pinning forces acting on trapped flux in a type-I superconductor [6]. Using high-resolution magneto-optics, in superconducting lead films, the number of trapped flux tubes (each containing 100–200 magnetic flux quanta) was counted as a function of a monotonically increasing applied transport current. Further, the critical current for the onset of flux flow was determined magneto-optically as a function of the applied perpendicular magnetic field, and was compared with theoretical curves obtained with different approximations for the interaction force acting upon a pinned array of flux tubes.

In the late 1970s, in Tübingen, we began scanning the surface of samples using the electron beam of a scanning electron microscope equipped with a low-temperature stage and recording a proper response signal as a function of the coordinates of the beam focus. This technique, subsequently referred to as low-temperature scanning electron microscopy (LTSEM), becomes particularly interesting when applied to superconductors. If the superconductor is in close thermal contact with a liquid-helium bath, the method can be used for a two-dimensional image of various sample responses arising from the localized excitation of the sample by the electron beam [7]. In this case, the strongly temperature-dependent electrical resistance of the sample provides an important response signal. For example, in the case of a current-biased sample, the beam-induced voltage change $\Delta V(x, y)$ can be recorded as a function of the coordinates (x, y) of the beam focus on the sample surface. In general, the spatial resolution of this imaging method is limited by the size of the local region heated by the electron beam. This “thermal healing length” η_0 depends on the properties and the geometry of the sample. In the case of a thin film of thickness d and thermal conductivity κ deposited on a substrate (which is closely coupled to the bath of the cooling liquid), the length η_0 is given by

$$\eta_0 = \left(\frac{\kappa d}{\alpha} \right)^{1/2} \quad (1)$$

Here α denotes the heat transfer coefficient between deposited film and substrate. In the case of the superconducting films we have studied, the value of η_0 is typically about 1 μm .

As proposed by John Clem and shown in Ref. [7], the spatial resolution of LTSEM can be increased significantly, if the electron beam is modulated at high frequencies ω and if the modulated signal is recorded. The underlying physics is referred to as thermal skin effect. The dynamic thermal healing length η is given by [7, 8]:

$$\eta = \eta_0 \frac{1}{\sqrt{\frac{1}{2} \left[\sqrt{1 + (\omega \tau)^2} + 1 \right]}} \quad (2)$$

Here τ is the thermal relaxation time

$$\tau = \frac{C d}{\alpha} \quad (3)$$

where C denotes the heat capacity per volume of the film. In the limit $(\omega \tau) \gg 1$, from (2) one finds $\eta \sim \frac{1}{\sqrt{\omega}}$. These theoretical results about the increase of the spatial resolution of LTSEM based on the thermal skin effect have been well confirmed by experiment [8]. Subsequently, these ideas were widely and successfully applied to high-temperature superconductors.

Concluding this brief summary, I emphasize again that we experimentalists benefitted greatly from John’s theoretical guidance.

References

1. Huebener, R.P., Kampwirth, R.T., Clem, J.R.: Meissner shielding currents and magnetic flux penetration in thin-film superconductors. *J. Low Temp. Phys.* **6**, 275–285 (1972)
2. Clem, J.R., Huebener, R.P., Gallus, D.E.: Gibbs free-energy barrier against irreversible magnetic flux entry into a superconductor. *J. Low Temp. Phys.* **12**, 449–477 (1973)
3. Huebener, R.P., Clem, J.R.: Magnetic flux structures in superconductors – a conference summary. *Rev. Mod. Phys.* **46**, 409–422 (1974)
4. Chimenti, D.E., Clem, J.R.: Current-induced flux motion in type-I superconducting films studied at 100 – ns time resolution. *Phil. Mag.* **38**, 635–653 (1978)
5. Clem, J.R.: Time-dependent voltage generated by flux motion across a superconducting strip. *J. Low Temp. Phys.* **42**, 363–371 (1981)
6. Pavlicek, H., Selig, K.P., Huebener, R.P., Clem, J.R.: Distribution of pinning forces on trapped flux in a type-I superconductor. *J. Low Temp. Phys.* **46**, 245–277 (1982)
7. Clem, J.R., Huebener, R.P.: Application of low-temperature scanning electron microscopy to superconductors. *J. Appl. Phys.* **51**, 2764–2773 (1980)
8. Pavlicek, H., Freytag, L., Seifert, H., Huebener, R.P.: Resolution limit due to thermal effects in low-temperature scanning electron microscopy. *J. Low Temp. Phys.* **56**, 237–257 (1984)