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SUMMARY AND CONCLUSIONS

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Looking back over this, the third IC SQUID conference, and trying to compare the state of our field now with the way it was at the time of the second conference in 1980, I realize that while there has been tremendous progress in some areas, in others there have been considerable disappointments and setbacks. In attempting to assess the many things that we have heard in the last four days, I will give some idea of the status of the various subdivisions of the field.

Let me begin with the basic building block of our technology, the tunnel junction. During the last five years there has been enormous progress in our understanding of the nonidealities that afflict junctions, for example, localized states in barriers, nonstoichiometric barriers, resonant tunneling, proximity layers between barrier and electrode(s), the diffusion of metallic overlayers into electrode grain boundaries, surface segregation, and the chemistry of barrier and counter-electrodes. Much of this progress has been achieved with the aid of some rather powerful tools of surface science, for example, ellipsometry, XPS, AES, RHEED and LEED. As a result of a great deal of hard work, we now have barriers that can be formed reproducibly to create Josephson junctions that are very stable and long lived, using, for example, amorphous Si, Al_2O_3 or MgO. One particularly impressive technology that we heard about was the all-NbN junction with a T_c of around 15K, fabricated with the SNIP process. Junctions of this kind with MgO barriers have rather impressive characteristics: V_g = 5.1mV, I_oR_N = 3.2mV and V_m = 69mV. An array of 1000 2.5 × 2.5 μm^2 junctions with a native oxide barrier showed a spread of only 1.6% in critical current, due, it was thought, to variations in the area of the junctions. Furthermore, these junctions could be boiled in water with no adverse effects!

I will turn next to some comments on research in basic physics, an area in which we have also seen a great deal of progress and excitement. One area of considerable activity is the study of nonlinear dynamics and chaos, where one takes advantage of the nonlinear current-phase relation of the Josephson junction. We heard several talks concerned with the rf driven junction, which is analogous to the sinusoidally driven pendulum and which has been studied in great detail both theoretically and in simulations. Although it is generally not possible to make an absolute one-to-one correspondence between observations on real junctions and a calculation or simulation with a particular set of parameters, nevertheless it appears that one can account for the observed features in a very satisfactory way. Furthermore, the insight that has been gained enables one to avoid regions of parameter space giving rise to chaos in the design of devices that are supposed to have very low noise.

Another fundamental area of considerable activity is macroscopic quantum tunneling (MQT) and associated phenomena. One type of experiment consists of measurements of the lifetime of the zero voltage state of a current-biased Josephson junction in the limit $\hbar\omega_p \gg k_BT$, where $\omega_p/2\pi$ is the plasma frequency; the decay of the metastable state is via tunneling through the potential barrier separating it from the free running regime. The observation of MQT implies that the macroscopic variable δ, the phase difference between two large reservoirs of Cooper pairs, obeys quantum mechanics. A related experiment involves a superconducting ring interrupted by a Josephson junction. In this case, the system tunnels from one stationary state to another; the macroscopic variable is the magnetic flux threading the loop. As we heard, there is an enormous array of theory for MQT, including the effects of damping and nonzero temperature. Now that experiments have been performed on current-biased junctions in which all the relevant parameters were measured classically, the existence of MQT seems to be unequivocably established. The results of an experiment on a loop containing an overdamped junction exhibited the T^2 dependence predicted for the exponent of the tunneling rate but a substantial disagreement with the predicted prefactor. More work is needed on the effects of damping. In a rather different kind of experiment, it was shown that the energy levels in a current-biased junction were quantized, a further confirmation of the macroscopic nature of δ. There was much theoretical discussion of macroscopic coherence (MQC), which, if observed, would demonstrate the superposition of two or more macroscopic wave functions. One candidate for MQC is the junction-in-a-loop, in which the system tunnels coherently back and forth between two stationary states. Another is a single junction in which, under appropriate conditions, the superposition of many states (corresponding to adjacent minima of the potential) may occur. If this latter situation can be observed, it would also have implications for standards, since it is predicted that in the presence of microwaves of frequency f one should observe steps in the current at intervals of precisely 2ef. The experimental conditions necessary for the observation of MQC are very difficult to achieve, but one might expect to see some efforts in this area in the next few years.

Some interesting physics was reported in arrays of junctions. Two-dimensional arrays in zero magnetic field have been used to demonstrate the Kosterlitz-Thouless transition. In the presence of an applied magnetic field, the flux lattice transition has been observed. One-dimensional arrays of junctions have been used to investigate nonequilibrium superconductivity: for example, two closely-spaced microbridges each containing a phase-slip center can interact via the charge imbalance generated by the phase slip process.

The final, very spectacular piece of basic physics that I'd like to mention is the observation of flux quantization, that is, of the Aharonov-Bohm effect, in normal metal rings. These observations involved the fabrication of extremely small gold rings, one with an average diameter of about 0.25 μm. The resistance was measured between two opposite points on a given ring as a function of the magnetic flux threading the ring. The resistance showed oscillations that were clearly periodic superimposed on a slowly varying background. The Fourier spectrum of these oscillations showed a large peak corresponding to a period h/e and a smaller peak corresponding to a period h/2e, both superimposed on background structure. As yet, it is not clear whether the h/2e peak represents a harmonic of the h/e oscillations or whether it arises from weak localization effects. This observation is most exciting, and much remains to be done both experimentally and theoretically.

Let me turn now to a brief review of the more applied aspects of the conference, beginning with SQUIDs. Work is very much focussed on planar, thin-film dc SQUIDs, with design criteria that have changed little since IC SQUID 80. These devices are fabricated using photolithography, and have small area junctions made with an overlap, window or edge technology. The rather low level of white noise that is now routinely achieved in these devices, typically a noise energy per hertz of a few hundred M, has emphasized the need to understand and reduce the 1/f noise that dominates at low frequencies. It has been found that a large variety of dc SQUIDs with quite different configurations exhibit 1/f noise with a spectral density $S_\Phi(f) \sim (10^{-10}/f)\Phi_0^2/\mathrm{Hz}$. Furthermore, at least for many of these devices, the 1/f noise arises not from 1/f noise in the critical current of the junctions but rather from an unidentified "flux noise". However, some devices fabricated recently at IBM exhibited substantially lower 1/f noise, for reasons that are not yet clear. Although the junctions in these devices may have been of exceptionally high quality with very low 1/f noise in the critical current, this does not in itself explain the reduced 1/f noise in the SQUID since the higher 1/f noise of many other devices did not arise from critical current fluctuations. It may be that the SQUIDs with low 1/f noise possess some other, materials-related property that is responsible. It should be emphasized that although one should certainly use junction technologies that produce low 1/f noise in the critical current (this requirement may exclude, for example, amorphous Si as a barrier), this is a necessary but not sufficient requirement for low 1/f noise in SQUIDs.

Considerable effort has been expended to develop schemes that enable one to couple input circuits efficiently to planar SQUIDs. Of these the most widely used is a superconducting, spiral input coil overlaying the loop of the SQUID. Other schemes involve coupling to a SQUID with multiple loops in parallel, the so-called fractional-turn SQUID, or the use of a double transformer to couple to a single-loop SQUID. Schemes like these have been used to produce a variety of SQUID-based instruments. There have been a number of first- and second-derivative planar gradiometers, intended for biomedical applications. A high-slew rate magnetometer with a thin-film pick-up loop has been operated successfully, and is intended for use in geophysical applications where the ability of the instrument to track fast transients is important. A radiofrequency amplifier based on a dc SQUID has been developed that has a very low noise temperature and can be operated at frequencies up to 300 MHz. A miniature susceptometer has been constructed that enables one to measure the susceptibility of micron-sized particles. Finally, there are several efforts aimed at developing multichannel, integrated instruments for biomedical applications.

Several applications of SQUIDs were described. A dc SQUID used as a radiofrequency amplifier has been used to detect pulsed nuclear quadrupole resonance (NQR) and to detect NQR using thermal noise with the spins either in equilibrium or in a saturated ($T = \infty$) state. In the more usual low frequency range, SQUIDs have been used to detect flaws in metals, to measure gravity gradients, to measure rotation and to detect the Schumann resonance. A single junction, rather than a SQUID, has been used to detect electron spin resonance. However, by far the most widespread application of SQUIDs discussed at this meeting was, of course, biomagnetism. This is a rapidly expanding field with many enthusiastic groups of workers, although it appears that biomagnetic techniques are still controversial in medical circles. Until fairly recently, the only available systems consisted of a single-channel second-derivative gradiometer ($\partial^2 H_z/\partial z^2$), that had to be moved to different parts of the head (for example) to enable one to obtain spatial information. As a result, measurements were slow and tedious. Fortunately, a system with five second-derivative gradiometers is now available, with three magnetometers and one first-derivative gradiometer for dynamical balancing, that is, electronic cancellation of ambient magnetic noise. In the future, one would really like to have 30 to 50 channels, so that large amounts of data could be taken in a short time. At this level of complexity, the wire-wound gradiometers presently used are likely to become rather impractical, and we heard considerable discussion of planar thin-film gradiometers. These devices measure off-diagonal derivatives ($\partial^2 H_z/\partial x^2$, for example), although a scheme has been proposed that may enable one effectively to measure the magnetic field, rather than a derivative, at a particular location. It is clear that there is a good deal of room for ingenuity in this field. One should not forget that there is an alternative approach, namely the use of a magnetically shielded room that presumably obviates the necessity of using gradiometers. Needless to say, such rooms are very expensive, and their use has not been widely adopted. Incidentally, biomagnetism is one application where a reduction in 1/f noise is of crucial importance, as is the design of an electronics package to produce a large dynamic range. It is encouraging to note that there is considerable commercial interest in the biomedical applications of SQUIDs, and this is one area that might just see an explosive growth in the next few years.

In concluding this discussion of the applications of SQUIDs, I should point out that only a very small fraction of the applications of SQUIDs is represented at this conference -- there is a wide range of experiments that require the sensitivity of a SQUID that were not discussed at this meeting. Overall, it seems that the SQUID business is in relatively healthy shape. However, I am more than a little surprised that a thin-film dc SQUID with an integrated input coil is not yet available commercially, although it looks as though this situation may change very soon.

Let me move on to high frequency applications. The preeminent device here is the SIS quasiparticle mixer, which is surely one of the success stories of superconducting electronics. A mixer has been operated at 36 GHz with a noise temperature of 3.7 ± 0.8K, a value within a factor of 2 of the quantum limit. A series array of N devices has been shown to have a noise temperature independent of N, and a dynamic range proportional to N^2, thereby enabling one to expand the dynamic range without sacrificing sensitivity. Mixers have been operated at frequencies up to 466 GHz, and have noise temperatures at least several times better than competing semiconductor devices. Under appropriate conditions the mixers exhibit conversion gain, thereby implying that they are operating in the quantum, rather than classical regime. Several groups are currently using SIS junctions on radio telescopes, and it seems that these devices will become the mixer of choice for all millimeter and submillimeter applications requiring the highest possible sensitivity. We also heard about the Josephson mixer, where the version with the internal local oscillator may still have some applications in the 600 to 2,000 GHz range, and the Josephson parametric amplifier, where the noise rise associated with the single-junction device has been eliminated by means of a inductive shunt with a resulting noise temperature of 6K at 10 GHz.

Interest in fluxon devices has grown rapidly in the last few years. These devices consist of a Josephson junction large enough to contain at least several flux vortices. In the flux-flow regime, a fluxon can be used as an oscillator in the 100-500 GHz range with a narrow linewidth and as much as 1 μW of power at an impedance level of 1 to 2 Ω. Such oscillations have considerable promise as local oscillators for mixers or parametric amplifiers. Another application of the fluxon is as an amplifier, where a gain of up to 200 has been demonstrated; such devices may be important in digital applications. Finally, we were treated to some beautiful pictures of vortices taken on the cold stage of a scanning electron microscope.

In my summary of IC SQUID 80, I said, "... one might hope to see ..., by 1990, a [Josephson] mainframe computer 10 to 100 times faster than the IBM 3030. Needless to say, the [junction] technology will also continue to advance ..." Well, the technology has certainly advanced a great deal, for example, with the advent of NbN junctions and Al_2O_3 and MgO barriers, but, of course, the very large effort at IBM to develop a computer was cancelled. It would be unrealistic to say that this has not been a major blow to the field of superconducting electronics. Nevertheless, as we heard, there is still a very impressive Japanese effort. It was projected that we would see 5,000 gates on a single chip with a cycle time of 700 ps in the near future. There is a considerable effort to develop alternative memory cells, for example, a vortex memory with non-destructive readout. Much of the effort in this field, however, is aimed at developing an alternative three-terminal device. Ideally, such a device should have voltage and current gain, high speed, input-output isolation, low power dissipation, a suitable impedance, and, above all, be manufacturable on a large scale. In essence, such a device would be a superior version of the semiconducting FET or bipolar transistor. Various devices have been proposed and tested, for example, the tunable weak link device, superconducting transistor, quiteron, magneto-electric device, single-fluxon device and the Josephson FET, but none of these devices looks terribly promising. Thus, although one should by no means rule out the possibility of a superconducting computer, particularly in view of the very fine Japanese effort, the time-scale required to develop such a machine now appears to be much longer than previously believed. Needless to say, the (semiconducting) competition will not stand still while a superconducting computer is developed and, as always, one must keep a wary eye on alternative technologies. One should not forget, however, that small scale superconducting electronics, for example A-to-D converters, adders and samplers, may still have an important role to play.

A quite different aspect of our field that continues to be successful is standards. The most important application here is still the use of microwave-irradiated Josephson junctions to maintain the standard volt. Just recently, a series array of about 1,000 junctions was used to produce a standard of about 1 volt, and it is expected that it will be possible to compare this with other voltage standards to a precision of 1 part in 10^9. Noise thermometry is of considerable interest. The Nyquist noise current generated by a resistor and measured by a rf or dc SQUID is a very useful secondary thermometer. The linewidth of the Josephson oscillations generated by a resistively shunted junction has been investigated in great detail and forms the basis of a primary thermometer. However, this thermometer is rather slow -- one is required to acquire data for about 1 day to achieve 1/10% accuracy at the 3σ level. Very recently, a resistive dc SQUID has been proposed as a noise thermometer. The proposal to use macroscopic quantum effects to relate current and frequency through the relation $I = 2ef$ would be of considerable interest if such effects are observable. By combining this equation with the Josephson voltage-frequency relation

$V = hf/2e$ and the quantized Hall effect relation $V = hI/e^2$, one would be able to check the consistency of the voltage, frequency and current standards.

The final topic I'd like to mention is cryocoolers. It has been long recongized that the advent of a relatively cheap, easy-to-use cryocooler would make superconducting electronics available to a much wider range of users. Unhappily, since IC SQUID 80 we have seen "basically disappointing progress". The requirements for a cryocooler are rather stringent: it should be extremely quiet both magnetically and mechanically, it should be very reliable with a long lifetime, it should be capable of continuous operation by unskilled personnel, it should be portable, it should preferably operate at 4.2K, and, of course, it should cost very little! In fact, existing machines still seem to be rather far removed from most of these requirements. The Stirling cycle machine reported five years ago reached ~ 7K, and has low enough noise for magnetocardiology, but probably not for magnetoencephalography. Existing models appear to have problems associated with contamination of the helium gas. A recent advance that may be very important, however, is the development of a sealed, ceramic compressor that has been operated for over 6,500 hours with no signs of contamination. Development of several Joule-Thomson machines continues: a four-stage refrigerator is nearing completion, while the miniature cryocooler consisting of microchannels etched in a Si chip has recently achieved ~ 19K. The latter device continues to look promising but very low levels of contamination are necessary to prevent clogging of the channels. It is not clear that a cryocooler meeting all or even most of the requirements is about to become available, but the importance of this technology cannot be overemphasized.

In closing this summary, I would remark that our field, at least as far as the applications are concerned, is in many ways at a turning point. Although Japanese industry appears to be willing to make a long-term committment to superconducting electronics, it is by no means clear that American and European industries share the same view. Relatively large sums of money are currently being invested in the U.S. to develop biomagnetic sensors and Josephson samplers for the marketplace in the <u>relatively near future</u>. If these projects prove to be commercially successful the whole field will benefit and expand. This could well happen if, for example, biomagnetic measurements become clinically acceptable. On the other hand, if these projects are commercial failures, the investors will cut their losses and pull out. As a result, I suspect funding in any area of cryoelectronics will be increasingly hard to come by, and the field will lose its impetus and vitality. Now there are a couple of ways, at least, in which I believe a group such as this one can help. First, we should direct our efforts towards improving existing devices or developing new devices that meet specific needs, and, needless to say, compete successfully with other technologies. Second, it is in many ways up to us to use our technology in new applications, so that new markets can be opened up. Unless there is a viable commercial future for any product, eventually it will disappear from the marketplace, and there is certainly no reason to believe that superconducting technology will prove to be an exception to this rule.

Finally, I should like to express the thanks of all us to the organizers of this IC SQUID conference. We are grateful to the local committee and their willing assistants for the usual superb organization that we have come to expect with regard to all the details that are necessary to ensure the smooth running of conference -- from the sending out of timely announcements to the organization of some 120 papers into oral and poster sessions and the arrangement of the reception and the excursion. However, as always, our warmest appreciation should go to Professor Hahlbohm who once again carried the overall responsibility for the success of the conference. Thank you very much.

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