In Memory of
Akira Tonomura

Physicist and Electron Microscopist

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Remembering Akira Tonomura

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Three of Tonomura's fundamental quantum physics experiments are discussed from a personal perspective.

My memories of Akira Tonomura are of a gentle and quiet man, always courteous in his dealings with colleagues, a virtuoso experimenter who transformed the electron microscope into the Stradivarius of scientific instruments, on which he played beautiful physics music. As a theorist I cannot comment technically on his many contributions. Instead I will make brief remarks about three of them.

The first is his demonstration[1] of the Aharonov-Bohm (AB) effect, intended to settle controversies associated with the inevitable failure of the idealization, assumed in elementary presentations of the effect, that the electrons are completely isolated from the magnetic flux. To eliminate leakage from the ends of a conventional finite solenoid, he confined the flux within a toroidal magnet, and to eliminate almost all penetration by the electrons he coated the toroid with a superconductor. The principle had been proposed by Kuper[2] (with the inessential difference that the magnetic flux would be confined in a hollow torus rather than a solid one). Because the flux in a superconductor is quantized (in units of $h/2e$), the experiment did not test the general AB effect, for which the flux is arbitrary; but it did demonstrate the important special case where the AB phase shift is π – as well as providing direct evidence of the value of the flux quantum (if this had been h/e there would have been no effect).

Even with a superconductor there is always some penetration of the electrons, so the flux cannot "completely shielded" as claimed in the title of Tonomura's paper. This is important, because as had been proved by Roy,[3] if there is any penetration, however small, the AB phase shift can be interpreted in terms of fields rather than potentials. Nevertheless, the fact that the phase shift remains finite as the limit of zero penetration is approached supports the usual interpretation in terms of potentials.. I commented on this[4] (in the same year – 1986 – as Tonomura's paper appeared) as an example of the need to be careful when considering idealizations in physics. Tonomura clearly appreciated the same point, commenting eloquently and wisely[1] "Since experimental realization of absolutely zero field is impossible, the continuity of physical phenomena in the transition from negligibly small field should be accepted instead of perpetual demands for the ideal; if a discontinuity is asserted, only a futile agnosticism results".

The second is his demonstration[5] in 1989 of electron two-slit interference, with the pattern developing gradually by the detection of individual electron impacts. This has been voted the most beautiful experiment in physics.[6] It illustrates convincingly and with the utmost simplicity the wave-particle duality that is fundamental to quantum physics. Its priority has been the subject of some controversy,[6] because the buildup of the pattern by individual electrons had already been observed in a pioneering experiment[7,8] by Merli *et al.* and published in 1976, together with an award-winning movie. However, as Tonomura points out,[6] his experiment improved on that of Merli *et al.* in several respects: (a) it had lower electron intensity (so the possibility of there being two or more electrons in the apparatus at any time is negligible), (b) it was sufficiently stable for the buildup to take place very slowly (during 20 minutes), and (c) it was sufficiently sensitive to detect the electrons with almost 100% efficiency. As with the AB torus experiment, Tonomura's demonstration was definitive.

The third is his creation of vortices (= phase singularities = nodal lines = wavefront dislocations) in an electron beam.[9] This was particularly gratifying to us in Bristol, where we have emphasized vortices[10] as generic singularities of waves of all types and have explored these topological features in detail theoretically[11-14] – including vortices generated by transmission through spiral phase plates,[15] exactly as employed in the experiment by Tonomura. His emphasis was on the orbital angular momentum carried by the vortex beam – an aspect much studied in recent years.[16] Almost all earlier experiments were carried out with classical light; the novelty of Tonomura's[9] was that it demonstrated vortices in the much more challenging quantum physics of electrons.

The Japanese government has agreed that the direction of research pursued by Tonomura will continue, and that is a welcome decision. Nevertheless the premature passing of this supremely talented experimenter leaves a sadness that is hard to overstate.

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