

NEUTRON INTERFEROMETRY:

A TALE OF THREE CONTINENTS

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In the 35 years since its first implementation, neutron interferometry has produced some fascinating demonstrations of quantum mechanics in action, has allowed the testing of a number of interesting quantum mechanical propositions and has allowed the precise measurement of physical quantities of vital importance in condensed matter physics.

This was one of the conclusions that emerged from the Vienna Symposium on the Foundations of Modern Physics held in June this year.

Organised by Anton Zeilinger, ably assisted by Markus Aspelmeyer and the staff of the Institute of Quantum Optics and Quantum Information (IQOQI) this Symposium, the 2nd in the series, also served as a Festschrift for Helmut Rauch and Danny Greenberger, noted experimental and theoretical luminaries in the field.

In particular, it was Helmut Rauch who, together with Wolfgang Treimer and Ulrich Bonse, was first to demonstrate the first Single Crystal Neutron Interferometer in 1974 [1]. Closely analogous to a Mach-Zehnder Interferometer in classical optics, these wonderful devices are carved out of a monolithic piece of highly perfect single crystal of silicon, of the kind used in the semiconductor electronics industry. A photograph and a schematic are shown in fig 1.

Three parallel slabs of silicon, connected by a base, contain perfectly aligned planes of atoms, which, by virtue of Bragg Diffraction, coherently split a beam of monochromatic neutrons, whose wavelengths are comparable in magnitude to the lattice spacing of the silicon crystal. Furthermore, the silicon is almost completely transparent to neutrons – so that absorption is essentially negligible. Thus, the first slab acts as a beam splitter, with a transmitted and a diffracted beam emerging from it. Both these beams continue to the second slab at which Bragg diffraction occurs once again. Ignoring the transmitted beams (which escape from the system), the two diffracted beams continue on their way to the third, equidistant slab, where they recombine in a way similar to the first beam splitter.

Although we have ignored the complex interplay of the beams inside the crystal slabs, which can only be calculated by using the dynamical theory of diffraction, by some miracle the three slabs of the silicon crystal act like the half-silvered mirrors in the optical interferometer.

Several centimetres separate the internal beams, but there is only one neutron inside the device at any given time. However, in the usual quantum mechanical prescription, it is impossible to tell which of the paths the neutron has taken – it travels along both paths at the one time!

The relative phases of the beams are influenced by inserting material slabs of different thicknesses inside the interferometer – in practice by tilting the one slab of material so that the beams traverse different thicknesses – and thus the interaction of the neutrons with the nuclei of the materials can be measured to a very high degree of precision. In effect this is a measurement of the refractive index of the material for neutrons that, in turn, depends on the scattering lengths of its constituent nuclei – important data in neutron diffraction crystallography. Rauch's and other research groups have performed a large number of such measurements over the years, using powerful neutron beams at the High Flux Reactor of the Institut Laue – Langevin (ILL) in Grenoble.

But no sooner was such a neutron interferometer constructed in Europe, a very similar one was produced in the USA, and the way was open for a large number of beautiful and fundamental experiments, each of them testing some aspect of quantum mechanics and exploring the fundamentally analogous behaviour of particles and waves, in fact doing macroscopic

▲ Acknowledgment to Gerry Lants, Australian cartoonist © Herald and Weekly Times, Melbourne, Australia.

wave-optical experiments with neutrons. Shortly after the demonstration of the first neutron interferometer by Rauch and his colleagues at the small research reactor of the Atominstitut in Vienna, Sam Werner and his colleagues at the Ford Motor Company Research Labs in Michigan (and later at Purdue University), designed and built similar devices and performed spectacular experiments with them. The competition was on!

Instead of just inserting material objects inside the interferometers one of the first experiments of the American group famously demonstrated the effect of the earth's gravity on the neutron beams inside the interferometer. In what has become known as the COW experiment [2] (after Colella, Overhauser and Werner) the interferometer was tilted about a horizontal axis parallel to the incoming beam. In this way, the two diffracted beams inside the interferometer become separated by a vertical distance and thus experience different gravitational potentials, by traveling at different heights above the earth's surface. The resultant phase differences become apparent in an interferogram plotted as a function of beam height difference. The measurement may be expressed using a formula that simultaneously involves Planck's constant h , and the gravitational constant g , the first macroscopic manifestation of a quantum-mechanical effect due to gravity. The next spectacular experiment was also one in which a field, instead of a material object, was to act on the neutrons – this time a magnetic field. But by then a third research group had entered the competition – this time from Australia. My late colleague Geoffrey Opat from the University of Melbourne and I, came across a paper by Aharonov and Susskind [3] proposing a gedanken experiment with electrons to demonstrate the peculiar behaviour of fermions, *i.e.*, particles with half-integral spin, when rotated by 360° about any axis: they do not return to their original state, like any macroscopic object, but develop a minus sign in their wave function. Up until then considered as merely a mathematical artifact, this minus sign is in fact crucial in explaining the Pauli exclusion principle that is responsible for the stability of ordinary matter. (The connection is explained in a side panel.)

To perform the rotation required in an experimental verification, a magnetic field is made to act on the intrinsic magnetic moment of the fermions, causing them to precess. The phase shift caused by the rotation can be made apparent in an interference situation; the minus sign, *i.e.* the 180° phase shift caused by an odd number of 360° rotations, will lead to destructive interference.

We immediately realised that neutrons would be needed to demonstrate the effect – electrons would be swept aside by the Lorentz force - and so did Rauch's group in Vienna and so did Sam Werner, who by this time had moved to the University of Missouri. As a matter of fact, a paper by Herbert Bernstein [4] published almost simultaneously

with the Aharonov – Susskind paper, explicitly suggested neutron interferometry to demonstrate the effect, several years before the first crystal interferometer was built.

That was the case for the Melbourne group too – we planned an interference experiment with neutrons in 1974 before we heard about the crystal interferometer, which in any case, we didn't have. Our experiment was based on interference by division of the wavefront, analogous to Young's two-slit experiment in classical optics. We proposed to diffract slow neutrons around a magnetic domain wall in a thin crystalline foil of iron alloy with the right properties. Having the right thickness would allow the neutrons to precess in the internal magnetic field inside the iron foil, so that the total precession angle would give an integral number of times 360° . For an odd number of revolutions, destructive interference should occur between the parts of the neutron wavefunction that traversed oppositely directed magnetic fields.

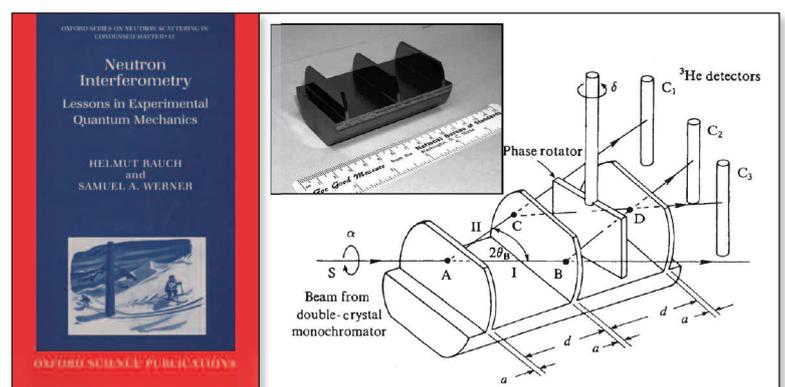
ILL accepted this proposal in 1974 and we published it in 1975 [5]. But by the time I arrived to perform the experiment, in September 1975, I found to my consternation that the corresponding experiment had already been done – by the Rauch group (using an electromagnet inside a crystal interferometer), as well as by the Werner group (using a permanent magnet). Their results, verifying this strange property of fermions, were published simultaneously in Physics Letters [6] and Physical Review Letters [7], in October 1975. We lost the competition for priority, but we went ahead and did our version of the experiment anyway – because it used a significantly different method. Our results, which also verified the theoretical prediction, ended up being published in 1976 [8].

However, what had started out as a competition between the three research groups on three continents turned into something completely different. Catalysed by the first conference on neutron interferometry, held at ILL in 1980, co-operative experiments followed for the next 20-odd years, with various combinations of participants.

The European and Australian groups co-operated on a series of neutron-optical experiments in 1979, including interferometry, and demonstrated the effect of the motion of materials inside a neutron interferometer – analogous to the famous experiments of Fizeau in classical optics [9].

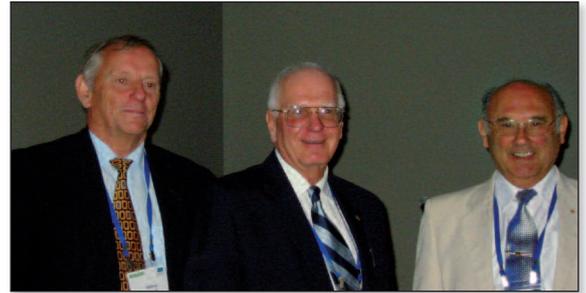
▼ **FIG. 1:** Schematic of a perfect crystal neutron interferometer. The output beams are counted in detectors C1 and C2 while C3 serves as a monitor of the total flux. The inset is an actual photograph of the monolithic silicon crystal device.

◀ **FIG. 2:** Cover of the monograph by Rauch and Werner (Oxford University Press, 2000). It contains details of 40 experiments and 1000 references. The picture is the famous New Yorker cartoon by Charles Addams that typifies the quantum mechanical behaviour of particles.



Meanwhile, the American group demonstrated the effect of the earth's rotation on the phase shift of neutrons – analogous to the experiments of Michelson and Gale in classical optics and only about 2% of the magnitude of their earlier gravity experiment. There followed a series of experimental collaborations between the Australians and the Americans in the 1980's further exploring the effects of the motion of matter on the phase shift of neutrons, demonstrating a null effect that depends on the velocity-independence of the neutron-nucleus interactions [10]. Later collaborations, in the 1990s explored a number of topological effects, analogous to the famous Aharonov - Bohm propositions in electrodynamics. The analogous effects for neutral particles, named after Aharonov and Casher, showed that moving neutrons can feel the effects of an electric field, in spite of being electrically neutral, because of their magnetic moment [11]. Furthermore, it became possible to demonstrate an analog of the so-called scalar Aharonov - Bohm effect that had hitherto not been observed with electrons [12]. The role of neutron interferometry in observing such geometrical and topological phases was reviewed in two recent conferences celebrating Yakir Aharonov and Michael Berry on the occasion of the 50th and 25th anniversaries of their discoveries. [13]

An unintended but felicitous outcome of the Australian – American collaboration was that my research student Bill Hamilton ended up marrying Sam Werner's research

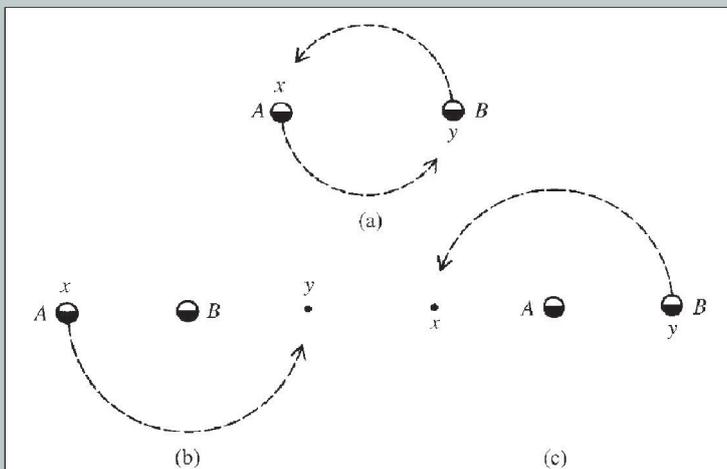


▲ FIG. 3: (Left to Right) The European (Rauch), American (Werner) and Australian (Klein) Collaborators.

student Mohana Yethiraj; both of them are now gainfully employed at the Australian research reactor OPAL after having been research scientists at Los Alamos and Oak Ridge National Laboratories for many years. The culmination of the European – American collaboration was the publication of a very interesting textbook on neutron interferometry, (Fig2.) in which the experiments that I described are fully elaborated along with many others and which, incidentally, contains all the references to the original publications. As quantum-mechanical playgrounds, neutron interferometers have thrown much light on the arcane mysteries of particles-acting-like-waves, over and above their role in precise measurements and experimental tests. The main protagonists (Fig.3), now happily retired, are proud of their achievements! ■

The Pauli principle explained

Feynman showed in an article entitled "The reason for antiparticles"¹ that the exchange of two particles (a) corresponds to each being rotated by 180° (b) and (c) *i.e.* 360° of relative rotation. If a fermion (*e.g.* electron, proton or neutron) develops a minus sign in the wavefunction when rotated by 360° then two identical particles in the same spin state cannot occupy the same position in space because they would interfere destructively if exchanged. Hence the Pauli Exclusion Principle! This "hand-waving" argument was put on a more solid mathematical footing by Michael Berry and Jonathan Robbins².



¹ In: 'Elementary Particles and the Laws of Physics' C.U.P. Cambridge, (1987)

² M.V. Berry and J.M. Robbins, *Proc. R. Soc. A* **453**, 1771(1997)

About the author

Professor Emeritus **Tony Klein** held a Personal Chair in Physics in The University of Melbourne until his retirement in 1998. He served as President of the Australian Institute of Physics (1990 – 91); Head of the School of Physics (1986 – 95); was elected a Fellow of the Australian Academy of Science in 1994 and was appointed a Member of the Order of Australia in 1999. He has published extensively in experimental physics, particularly about neutron optics.

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