P.R. IN QUANTUM HALL EFFECT TWENTY AND THIRTY YEARS LATER

A previous article [see rf.8] delineated some conceptual complications that have arisen in the wake of a striking display of quantum order known as the quantum Hall effect [1], first discovered in 1980. In its so-called plateau states the nature of this effect is a mixture of induced superconductivity and a one-parameter discreteness of its Hall impedance Z_H depending on charge injection. This led to a second discovery revealing a new (fractional) quantum number for flux injection [2]. Their common Klitzing constant h/e^2, in conjunction with the constant h/e of the Josephson ac effect led to more consistent *e* and *h* values earlier obtained from other basic relations including quantum electrodynamics.

In 1980 the integer effect came about by charge injection *se* in the 2-dimensional interaction space of the Hall effect and two years later the fractional effect was discovered by magnetic flux injection [2]. From that point onwards the experiments seemed to be homing in on a simple and an for all practical purposes very precise empirical formula:

$$Z_H = \frac{n}{s}\frac{h}{e^2}; \; n \text{ and } s \text{ integers.}$$

A justification of this equation from experimental- to exact result has been a major theoretical challenge though. One can at best say taking experimental values of Z_H and combining them with earlier QED values for *h and e* the parameters n and s came out as *near* integers. So taking this formula to be exact was an act of judgmental daring that led experimentalists to a set of *h* and *e* values more consistent with overall existing data.

The discrete Hall impedance shows itself here as a ratio of flux *nh/e* over charge *se*. Since the Aharonov-Bohm paper [3] of 1959, the expression *nh/e* has been known to equate a cyclic integral of the four-potential *A*. In fact two years later two seminal experiments by Doll *et al* [4] and Fairbank *et a*l [5] showed the smallest flux quantum to be *h/2e* not *h/e*. If until that time quantization of flux had still been somewhat in question at this point, despite rumors of fractional charge, there is little doubt that quantization of charge as based on electronic charge is now well established. In fact it should be accepted as the first basic manifestation of quantization that became apparent after Faraday established the precise laws of electrolysis.

In the light of these introductory remarks, making a transition from the pre-quantum era to the quantum era of the quantum Hall effect it would seem almost impossible to ignore the 1961 experiments [4,5] substantiating flux quantization and the longer known fact of charge quantization. Their application then immediately establishes the Hall effect formula here displayed except for factors 2 or 4 in the denominator to account for the cited transition *h/e*→*h/2e* for the flux and/or s→2s for the Cooper pairing of the charge carriers needed to account for an induced superconductivity manifest in these experiments. Indeed an observed dominance of odd enumerator values n cited for these experiments [2] supports this simple theory approach. It is indicative of an ordered matrix of identical cyclotron configurations sliding through the 2-dimensional interaction space of the Mosfet experimental sample. The cyclotron states are even numbers of electrons together encircling an integral number of flux units h/2e, The boson character of Cooper pairs permits accumulation in a same orbit through a BCS-type mechanism in which repulsive orbital forces are being converted into attractive interactions due to adjoining Mosfet layers defining the space of interaction.

It can hardly be denied that this string of arguments using experimentally proven flux- and charge quantization plus BCS type conditions accounts for a joint manifestation of what are now known as integer and fractional effects as well as the state of induced superconductivity and ensuing dominance of (reduced) odd valued quantum numbers n. This quantized flux over quantized charge procedure for the quantum Hall effect was a topic of correspondence between Robert M Kiehn and me in the fall of 1981. It simply notes that the effect can be described as a ratio of the Aharonov-Bohm- and Gauss integrals appearing here as counters of flux- and charge quanta. In retrospect it meant the two quantum number account opened up an option of accommodating the fractional Hall effect [6] already in the making prior to its explicit discovery at Bell telephone [2].*

However, the major theoretical development that followed did not avail itself of a then already existing independent evidence of non-statistical single system flux quantization. Instead a vast majority was seeking insight through Schroedinger's statistical process operating on a Hall situation that seemed an epitome of order. Notwithstanding this discrepancy between tool and object of investigation this pursuit went ahead and led to a dichotomy between integer and fractional quantum Hall effects clearly contradicting empirical experiences with the here cited formula. From the beginning Bell Telephone Labs emphasized the fractional effect as fundamentally different from the integer effect. An avalanche of papers using Schroedinger-based procedures came with new propositions ranging from actual fractional charge to composite fermions.

It became increasingly difficult getting a word in on using period integral ordering for a unified flux and charge quantization. Kiehn tried to come to the rescue in Physics Today [7] and by placing the preceding write-up on the Internet [8] about the 1987 Nobel award. The latter awarded the discovery of an important new aspect of the Hall effect, yet by association it is now also taken as an approval of its version of theory. Now almost thirty years after the discovery of the integer effect, this stand-off between Copenhagen Doctrine and the Aharonov-Bohm option is keeping alive a silent suggestion that Schroedinger's process is still the one and only primary quantizer in nature, in which it is taken for granted that this quantizer somehow happens to be (non-classically) statistics-based.

In the light of the here cited experiences it now needs to be said that this silent aspect of Copenhagen Doctrine needs to be rejected. A paper by Kiehn [9] must be regarded as instrumental in this transition. It shows how the *existence* of Aharonov-Bohm and Ampère-Gauss integrals, and Kiehn's product integral thereof, are equal to multiples of topological invariants using de Rham's existence theorem [10]. This was known to be true for Gauss' law and its topological constant equal to the electronic charge, now according to de Rham and Kiehn it is the basis why the Aharonov-Bohm integral equals multiples of a topological constant which has now been measured to be *h/2e* in the refs.[4, 5].

Since 1959 a vast majority in physics has been silently suspect of the Aharonov-Bohm integral, which in reference to Ψ single-valuedness equates to multiples of *h/e*. In the light of Kiehn's appeal to de Rahm's existence theorem and the experimental confirmations by Doll[4] and Fairbank [5] the smallest period of the integral would be *h/2e* instead if *h/e*. So except for a factor 2 Kiehn's move to de Rham theory considerably strengthens

i

* In fact a note to this information was inserted prior to printing in a paper on the esthetics of physical dimensions and invariant quantization features [6].

the AB position to the point that casting suspicion on a legitimate law status of the AB integral is truly out of order. By the same taken it strengthens the empirical Hall effect formula except for a factor 2. Even so the unification of integer and fractional effect is there, so is the induced superconductivity either by this factor 2 or and by the alternative of even quantum numbers s due to Cooper pairing. At this point the global integral approach is way ahead of its Schroedinger-based alternative supported by that vast majority still caught in its dichotomy, seeking artifacts accounting for the fractional effect, while still negating the observed super-fluidity.

The above paragraph summarizes in the briefest possible manner a compatible delineation of a slightly revised Aharonov-Bohm law as single system tool with a revised interpretive picture for the Schroedinger process. They are here presented as unavoidable change for a unified more sensible account of the quantum Hall phenomenon while at the same time clearing up some long time problems associated with Copenhagen Doctrine.

In more normal circumstances it would suffice to conclude Copenhagen Doctrine and its nonclassical Ψ statistics has to change instead. An ensuing reformulation of quantum mechanics as an ensemble reality in the sense of Karl Popper had already emerged in the mid Thirties. A 1995 monograph entitled *Quantum Reprogramming* [11] takes up this initiative of the Thirties while pleading in addition to replace Copenhagen's ***nonclassica***l Ψ statistics by a ***classical*** statistics. So far no reviews have commented on its radical rejection of Copenhagen Doctrine or its global treatment the quantum Hall effect.

Since the two topics are contingent it is important to mention that any open forum discussion of these matters has been impossible perhaps in fear of ref.3 published half a century ago. Instead of communicating there has been an atmosphere of mutually ignoring one another, an attitude that has been insulting and truly does not help anybody and least of all the subject matter. The fact is for three decades that vast majority pursuing Schroedinger-type approaches has never felt a moral obligation of at least acknowledging the existence of a unifying Aharonov & Bohm-based approach. The fact that this publication anomaly could be maintained for thirty years is scary evidence of a shameful secretive clique mentality in US physics. All brought to the fore by an apparent PR move of exaggerating claims about the fractional Hall effect being totally different. The longer this lasts the more misgivings pile up of festering divisions, disrespect universal pessimism and distrust in those responsible for the decorum in American physics.

It is high time to clear up a half-century old conflict concerning Aharonov and Bohm. I will admit my use of their integral on the quantum Hall effect testifies to a good measure of naïve confidence. I do believe though that an added appeal to BCS principles finally gives my naivety the benefit of the doubt over Copenhagen Doctrine. Finally a word of thanks and apology to Robert Kiehn [9] for his appeal to de Rham theory lifting much obscurity surrounding the AB integral; the apology is for my aesthetic pursuit [6] failing to refer to his lifting [9] of period integrals into the light of a new dawn of physics.

So far Robert Kiehn and I have been unable to agree about whether or not or how to descend into the particle domain using period integral considerations [12]. His considerations though attempt to cover irreversibility, facing quantum Hall reversibility I have not been reluctant calling on Cartan [13] to accept these period integrals as metric-independent general invariants. Since the metric is the one and only criterion giving us a sense of size, it can now be argued that a metric-free law cannot impose inherent limitations of applicability in the micro-domain. Therefore an orbital Aharonov-Bohm situation in an external field conjoins a time- and space loop which can only meet the period integral condition if and only if the topology of the orbiting object (e.g., electron) permits a field-free interior E=B=0. It means a period integral condition of orbital particle behavior in external fields is contingent on how the particle's internal topology matches with the topology of the external field. Here is another factor 2 joining the fray; it is the factor 2 discovered by Doll and Fairbank. In the same issue of [4.5], it was Onsager who identified that factor 2 as the one of Cooper pairing. Yet their conceptually totally different origin does not make that a foregone conclusion. Chances are some imaginative experimentation can now give us not only the ratios *n/s* but also products *ns*, providing insight into their real magnitudes and associated mechanism.

While this global alternative to the quantum Hall effect is still incomplete, its very incompleteness still holds down to earth keys for a conceivable correction or rejection. As the author of these lines I am of course prejudiced in my opinions, yet after 30 years dare I say this alternative still compares favorably to that legendary statistical approach to a globally compact physical manifestation without any hint of anything statistical going on. If the latter move turns out to be a mistaken initiative of the late Bell telephone Laboratories, the birthplace of so many constructive contributions to society, let it be known how this very move also brings out overdue changes in Copenhagen Doctrine.

Even so, the more amazing conclusion emerging from the here-cited experiences is not physical in nature. Throughout history the exact sciences have been known for requiring great penetrating inquisitiveness of looking behind the facts yet balanced by a strict discipline of facing reality with unwavering honesty.

Thirty years of quantum Hall history have shown how a vast Schroedinger majority has shown discipline beyond the call of duty in putting that one and only tool to work that Copenhagen had left them. While that earns them an A for discipline, it leaves a C- for inquisitiveness and a D for integrity in facing reality with unwavering honesty. The majority approached the QHE in a spirit of using Copenhagen's nonclassical scheme. That process has served in the past yet moral obligation remains of acknowledging simpler unified alternatives, lest physics appears all learning and no understanding. Over the past thirty years papers dealing with a unified alternative only appeared outside the US! Since Bell Labs insisted on an integer-fractional dichotomy, APS honor demands some explanation how its reviews have been so amazingly uniform over the past thirty years. These convolutions are not mine, yet they need to be cited to disentangle an ugly situation.

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