Minicurso: Seeking rigor in the interpretation of Quantum Physics.
Número de horas: 8 horas
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Filiação: IBM - EUA

Programa resumido:

1. The theme

This course is about the interpretation of Quantum Physics (QP), by which is meant the physics at small scale when relativity can be mostly neglected, by which we mean essentially the Realm of application of Quantum Mechanics (QM) that is a well formulated theory (in a couple of detailed forms) that is the essential tool of theoretical QP.

By the distinction between QM and QP, we mean in particular that sticking to the canons of MQ is not considered as a priority, although all efforts are made to stay alined with QM whenever possible. Since physics is known for instance to require relativistic corrections in some regimes, it is to be expected that QM be at most tangent to QP, and since QM was formulated on the basis of some experimental data, nothing can guaranty a priori that enlarging the set of experiments will not force some departure, hopefully quite small either from QM or from the way it is used in theoretical QP.

At least one of the formulations of QM, due to von Neumann, stands in all mathematical rigor since 1932, about five years after the papers that stand as the original expression of QM (Heisenberg, Shrödinger, Dirac, Born, Jordan between 1925 and 1927) got written after the foundational works of Planck, Einstein, Bohr, Sommerfeld, de Broglie, etc. and with additions by people such as Ehrenfest, Pauli, Wigner, etc., altogether occupying the 30 first years of the twentieth century. On the other hand, Dirac's formulation as it appears in his book published in 1930 certainly has at least all the rigor physicists usually expect from a completely coherent theory.

Despite this encouraging facts, the interpretation of quantum mechanics has turned into several competing interpretations, some of which for the least incomplete, some other in direct conflict with what some physicists consider as basic laws of Nature. We take the viewpoint that the formulation of the interpretations so far have lacked the level of rigor of QM itself (as will be illustrated by important examples during the mini-course), in some cases because a priori philosophy stands were taken. There are of course noticeable local counter-examples such as the discussion of the EPR paper in [9].

2. Review of quantum mechanics: the basic Postulates and some comments.

We will review the very basic elements of quantum mechanics, assuming some minimal familiarity with Hilbert spaces and related concepts: in fact understanding of the elementary theory will essentially suffice despite the fact that QM needs continuous spectra. In fact, the mathematical level will be fixed as what is needed to understand the formal part of a famous 1935 paper signed by Einstein, Podolsky, and Rosen which did not get Einstein's imprimatur but whose weaknesses are usually amplified and then most often attributed to Einstein.

3. Revisiting some classics.

Once the Postulates of QM reviewed, we will study two important historical papers [8], [1] and some of the related literature:

- A) the EPR saga and in particular:
  - A1) The paper of Einstein, Podolsky, Rosen [8], often called simply EPR, and Bohr's response [4]
  - A2) The versions of Einstein of what he considered essential in the discussions that lead Podolsky to write EPR as reported by Fine [9] as well as some of Einstein's own versions that came to print [7], [14].
  - A3) The account of EPR in Bohm' book [2], the paper of Bohm and Aharonov replacing the spin-$\frac{1}{2}$ particles of [2] by linearly polarized photons [3],
- B) The paper of Bell about Bohm, presented by Bell as a [discussion of] or [comment upon] EPR [1] and some further papers that with [1] constitute a basic part of what one can call Bell's type theorems [6], [11], [12], [10].
- C) A couple of papers replacing the locality hypothesis used by Bell and other in Bell theory by a weaker hypothesis.

We will identify the main issues, the main techniques and in particular *realism*, one of the two hypotheses used, in some form, to prove any Bell type theorem. We will recall the classical pre-history of Bell's paper, Boole's Theory and define Bell Theory as the conjunction of:
- Boole's theory (indeed unknown to Bell),
- A pair of physical hypothesis about Quantum Physics, whereby Quantum mechanics is complemented by some form of *realism* and *locality.*

The proof of Bell's inequality in the original and CHSH forms will be recalled as well as the proof of GHZ (also known as "Bell's theorem without inequalities") in the usual form, *i.e.*, when assuming both *realism* and *locality.* This permits one to conclude that assuming both *realism* and *locality* is incompatible with QP, and we will briefly discuss experiments that have been performed in order to confirm that point.

4. Bell's theory without Locality and more evidence against realism.

We will then replace Locality by an hypothesis, called the Effect After Cause Principle (EACP) that will reveal not only as weaker than Locality, but also as mostly being noting else than Causality but adapted to prevail as well when assuming realism to hold true. The new set of hypotheses will let us prove forms of the GHZ and Bell's theorem, inviting strongly to the conclusion that realism BY ITSELF is incompatible with QM [15], [16].

We will then have recourse to simple but carefully designed experiments that directly support that realism should NOT be part of QP. From there, with further recourse to the same experiments and a few other ones, we will formulate a mostly complete interpretation that avoids many of the traps, difficulties, bizarre aspects and counter-intuitive aspect etc. of other interpretations.

Not all is made comprehensible but an intuition presented by Riemann in his habilitation help one understand that parts of the interpretation cannot be imagined nor understood as can be aspects of science at the macroscopic scale. While this intuition of Riemann poses huge mathematical challenges, it cannot be held as a necessary ingredient to the interpretation of QM. Nor does this direction constitute the only avenue for new mathematics in the context of modern QM. We will mention the openings that constitute Quantum Information and perhaps also Quantum Computing, and point out the some places where realism is invoked or false call are made upon Bell's theory.

It may seem strange to put so much emphasis on realism *vs* non-realism. To give a feeling of why this is such an important issue (that indeed conditions a large part of the interpretation of QM), we recall that traditional QM was vastly predominantly non-realist but that most authors (most often inadvertently) have failed to be faithful to their expressed commitment to non-realism.

Remark 1: Realism is indeed strongly entrenched archaism that is difficult to let go, inasmuch as it seems so self evident at macroscopic scales: if the answer to the question "Is the moon there when you do not look at it?"seems so obvious that it takes a serous personal cultural revolution to admit similar questions to have a negative answer when raised about microscopic objects. The hiatus between the microscopic and macroscopic seems at first sight to be a blow to the opinion that the Realm of QM is NOT limited to microcosm and a few noticeable exceptions in the macroscopic world.

Remark 2: To the contrary of his entrenched status of realism, the status of Locality is purely intellectual since with an infinite speed of light, causes could travel instantaneously to the end of the Universe. To our day to day perception, the speed of light might well be infinite and Rømer had difficulties convincing the scientific world when he computed the speed of light as large but finite. Cassini who was then the head of the Observatory of Paris, hence Rømer's boss ended up believing that the speed was infinite while he was probably the first one to have measured it as finite.Anyway, he permitted Rømer to publish his finding [13].

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II. Cited Literature

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III. Some Other Books

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