IL NUOVO CIMENTO **47 C** (2024) 341
DOI 10.1393/ncc/i2024-24341-3

COMMUNICATIONS: SIF Congress 2023

A comparison between the First and the Second Quantum Revolutions: Development of a teaching course for secondary school students

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received 30 January 2024

Summary. — We are now experiencing the Second Quantum Revolution. It follows a first one that took place at the beginning of the XX Century and from which the fundamental idea of wave-particle duality was born. During the last century, this revolution led to the development of some technologies at the base of modern society like transistors and lasers. The Second Quantum Revolution is giving rise to new kinds of technologies such as quantum sensors, quantum communication protocols, quantum computers and quantum simulators. It is changing the world we live in and, as educators, we are called to promote quantum literacy and contribute to preparing the next generations of experts. In the present contribution, we present a teaching module on these themes targeted at high school students that aims to introduce some basic concepts and ideas to grasp what quantum technologies are, as well as foster a reflection on the cultural and conceptual scope of the ongoing revolution.

1. – Introduction

The field of Quantum Information Science and Technology (QIST) is one of the pillars of research and development and an integral part of the strategic agenda of many countries like Europe, the UK, China and the U.S. The Second Quantum Revolution is impacting not only scientific research, but also politics, society, ethics, economics, the environment as well as education. As initiatives like the Quantum Flagship or the National Quantum Initiative highlight, also the field of science education research is involved. Among the different objectives, science education research is called to contribute to four main goals: i) facilitating the creation of new ecosystems in which universities, enterprises, and schools can dialogue; ii) widening the workforce by running programs also for non-physics students; iii) attracting new generations of quantum experts and iv) promoting quantum literacy [1, 2]. In this landscape, the research group in physics education at the University of Bologna started to work on quantum technologies in 2018

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within the Erasmus+ project I SEE, which ended with the development of a first draft of a module targeted at secondary school students. From the first implementation in 2019, the module was iteratively refined according to a Design-Based Approach [3] and implemented also with pre-service and in-service teachers. In this contribution, we introduce the module and the approach developed in these years that has the overarching objective to introduce the ongoing revolution and the emergent technologies without missing the opportunity to reflect on their cultural and conceptual scope.

2. – An educational approach to the Second Quantum Revolution

The teaching module has been designed to enrich the narratives that are often used to talk about the Second Quantum Revolution. Such narratives usually focus on the great potential of quantum technologies to solve problems that have never been solved before because they are too complex (for example, problems that require exponential time to be solved) or to "crunch millions of calculations at the same time". These narratives often rely on computing power, on the possibility of carrying out much more precise measurements through quantum sensors, shedding light on the "magical" character of quantum technologies. These narratives are very effective for engagement, but they risk hiding the cultural significance of the ongoing revolution. As Gisin [4] wrote: "We are living in an extraordinary age.[...] The conceptual revolution taking place today is [...] completely overturns our previous pictures of nature and will doubtless give rise of new technologies that will simply look like magic". He continues: "Had we lived at the time of the Newtonian revolution, would we have wished to understand what was going on? Today quantum physics gives us the opportunity to live through a conceptual revolution of similar importance" [4]. Gisin's position inspired the formulation of the core questions that guided the search for the approach to introducing the Second Quantum Revolution for secondary school students: what characterizes the Second Quantum Revolution with respect to the First one? What is its cultural and educational potential? How can we design educational materials able to value the Second Quantum Revolution also beyond the technical training? To contribute to these questions we systematically apply a compare and contrast principle. First of all, the principle was implemented to individuate the differences and the commonalities between the First and the Second Quantum Revolutions, in particular from conceptual, epistemological and experimental perspectives. Following the work of Aspect [5], the two quantum revolutions revolve around two different concepts: on one hand complementarity and, on the other, entanglement. Both concepts firstly represented a conceptual challenge, conceived and discussed through thought experiments: the complementarity in the Bohr-Einstein debate about the nature of the quantum object, and the Bohr-Einstein debate in 1935 about the completeness of quantum theory and its non-local character. Both the conceptual challenges became also experimental challenges, the hypotheses that lived in the laboratory of mind were reformulated to be tasted experimentally. The two fundamental experiments were the double-slit experiment on one hand and the experiment realized by Aspect that proved the violation of Bell's inequalities [6]. Secondly, the compare-and-contrast principle was applied to confront the logic behind the functioning of the hardware of the classical and quantum computers, that is the binary and the quantum logic. Finally, we implemented the principle to compare the foundational experiments and the circuits. This idea develops the basic idea that characterizes a physical approach to quantum information expressed by Landauer and then stressed by Preskill: "Information, after all, is something that is encoded in the state of a physical system; a computation is something that can be carried out on an actual physically realizable device." [7]. The compare-and-contrast principle is applied to the confront of experiments and circuits by reconceptualizing the three main phases of an experiment (state preparation, state evolution/manipulation, and measurement) in terms of input-processing-output information [8]. In the next section, we present the teaching module that was iteratively refined following a Design-Based Approach [3].

3. – The module

The module was implemented 5 times as an extracurricular course with high school students and one time as a teachers' training course. It lasts 18 hours and consists of 6 meetings of 3 hours each. In the final version of the module, the first meeting is dedicated to the First Quantum Revolution. We introduce it first as an experimental challenge, that is the realization of the double-slit experiment with electrons (or, more in general with single quantum objects) that, as Feynman *et al.* discuss, "has in it the heart of quantum mechanics [...] it contains the only mystery" [9]. The experiment was realized for the first time by Merli, Missiroli and Pozzi [10] and has been awarded as the "most beautiful experiment" in 2002 by the *Physics World* journal [11]. Then, students are exposed to the historical and conceptual debate between Bohr and Einstein on the double nature of light, electrons, and matter that took place during the Solvay Congress in 1927 (Electrons and Photons) and the debate between Schrödinger and Heisenberg about the problem of visualization in quantum mechanics. Through a simplified spin-first approach and the Stern and Gerlach experiment, the quantum object is then re-conceptualized and formalized through Dirac notation as well as the concept of state manipulation and quantum measurement. In the second meeting, we address the Second Quantum Revolution and the second mystery of quantum physics, the entanglement. In particular, we introduce the very well-known Bohr-Einstein debate in 1935, when two papers with the same title were published: "Can quantum-mechanical description of physical reality be considered complete?" [12, 13]. The debate revolved around two aspects that Einstein had trouble accepting: the probabilistic-statistical character of quantum theory and its inherent non-locality. Following a historical approach, we briefly introduce the hidden-variable theory, the work of Bell and his reformulation of the Einstein-Podolsky-Rosen argument in mathematical terms, Bell's inequalities. Bell's re-conceptualization transformed the argument into a testable hypothesis experimentally. We then introduce the experiments of Clauser, Aspect and Zeilenger about the violation of Bell's inequalities and the experimental challenge they had to address. The last part of the second meeting is dedicated to the introduction of the new era of technologies that these foundational experiments contribute to generating: quantum simulations, quantum computers, quantum communication and quantum metrology. Particular attention is paid to the applications and implications of quantum technologies on research, politics, society, economy, ethics, environment and education. After the introduction of the two quantum revolutions, the focus of the third day is the physical nature of information. We start with a brief history of classical computers introducing the logic at the basis of their functioning and the physical systems that can realize it. Moving to quantum logic, we recall the Stern and Gerlach experiment and re-read it in terms of information, introducing one-qubit system, quantum logic gates to transform the state, quantum measurement and some examples of circuits. The fourth day is dedicated to two-qubit systems and entanglement. As in the case of the one-qubit, we introduce the state of two-qubit system, its manipulation through quantum logic gates, and some examples of circuits. The idea of entanglement is formalized through the four Bell's states. In the last part of the meeting, we introduce the first example of technology, the B92 quantum cryptography protocol. On the fifth day, we address a second example of quantum technologies: the teleportation protocol. We start by discussing one of the first experiments realized by Zeilinger and colleagues in 2004 in which they teleported the state of a qubit across the Danube River [14]. We then re-read the experiment in terms of information, that is by comparing the experiment with circuital representation [9]. The last day is dedicated to teamwork activities in which students explore the scope of the ongoing revolution and how it is changing the world we live in.

4. – Conclusion

In this article, we briefly presented the main ideas that guided the design of a module for secondary school students on the Second Quantum Revolution. The module is the result of a process that consists of back-and-forth dynamics between educational hypotheses and empirical results [3]. In the past, the analysis of the data showed the educational potential of a computational approach to quantum physics as well as the risk of oversimplifications that can lead students to consider the theory mainly as a tool for calculating. The preliminary results of the last implementation [15] suggest instead that the compare-and-contrast principle promotes the design of a learning environment properly complex [16] in which students could perceive the epistemological and cultural scope of the Second Quantum Revolution.

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