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Walking in the Quantum World: The Italian Quantum Weeks Exhibition 2024

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Summary. — In the context of the Italian Quantum Weeks initiative, the exhibition "Dire l'indicibile" proposed a journey through the rules of Quantum Mechanics, offering a glimpse at the working principles and potential applications of quantum technologies (QTs). We devised a route to introduce the key concepts of quantum superposition, quantum measurements and evolution, and incompatible observables, by exploiting analogies based on custom-made models and tools. As examples of possible QT applications, we choose to discuss: i) the peculiarities of quantum walks (QW), as compared to classical random walks; ii) quantum cryptography and its applications. Two activities —illustrating the basis of QWs and of the BB84 quantum key distribution protocol— were actively performed by the public. The outcome of a satisfaction survey is extremely positive, encouraging us to explore this approach in different educational contexts.

1. – Introduction

In recent years, the emergence of quantum technologies has boosted the number of both educational initiatives [1-3] and popular accounts regarding Quantum Physics (QP). The latter often prioritize its counterintuitive and puzzling aspects over a clear exposition of the foundational principles of QP. Physics education is therefore faced with the challenge of simplifying quantum concepts without compromising their essence, aiming to bridge the gap between complex scientific truths and public understanding. In this context, the interactive exhibition, "Dire l'indicibile" ("Speaking the unspeakable"), designed within the Italian Quantum Weeks project [4], strives to make QP comprehensible to everybody, using the natural language and examples from everyday experience, but avoiding the pitfalls of oversimplification and inaccuracy. The visitors of the exhibition are introduced to the basic concepts of QP, *i.e.*, the definition of quantum states, superposition, quantum measurements, the non-commutativity of observables, entanglement,

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through visual analogies and *ad hoc* designed demonstrators. Explicit reference to key results, such as Feynman's double slit and Stern-Gerlach experiments, are used to connect abstract concepts to physical evidence. Details of this path can be found in [4] and will be extensively described elsewhere. In this paper, after introducing the Quantum Cards —one of our *ad hoc*-designed educational tools— we briefly illustrate two staging activities that have been part of the exhibition and are used as embodied tools to improve not only engagement but also understanding and memory retention [5]. The *Quantum walk activity* is designed to illustrate the idea of how quantum evolution can differ from its classical counterpart (random walk) and can be exploited to obtain novel quantum algorithms [6]. The *BB84 protocol activity* not only offers an insightful glimpse into quantum cryptography [7], but also provides a striking example of how the apparent limitations of quantum physics —such as the existence of non-compatible observables and the measurement problem— can actually be turned to our advantage.

2. – The quantum cards tool

Non-commuting observables represent one of the central concepts of quantum physics that our exhibition seeks to explore and clarify. To illustrate this concept, we have developed a novel educational tool called the Quantum Cards (QCs). As shown in fig. 1, a QC features two dichotomous observables: the color of the back (blue or red) and the court figure on the front (queen or jack). The QC flipping halves allow to represent either a superposition state or an eigenstate of the two observables. Additionally, when one observable is in an eigenstate (*e.g.*, red or blue), the other is unavoidably in a superposition state (*e.g.*, queen and jack) —and *vice versa*. Measurement causes the card to collapse into an eigenstate of the measured observable, while the other observable enters a superposition state. These specially designed tools are used throughout the exhibition and play a central role in the BB84 activity.

3. – The BB84 activity

This activity begins by introducing cryptographic keys using the simple example of Caesar's cipher. The BB84 protocol for secure quantum key distribution [7] is then explained, engaging the audience with the QCs described earlier. Alice selects a sequence

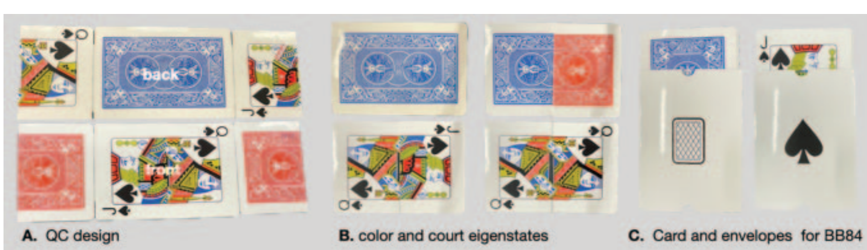

Fig. 1. – (A) A QC is made of a main body (blue on the back, half-queen half-jack on the front), to which are attached two flipping half-cards (both red on the back, either half-queen or half-jack on the front). (B) Examples of eigenstates of one observable ("blue" on the left, "queen" on the right), corresponding to superposition states of the other. (C) In the BB84 activity, after preparation, each QC is placed in an envelope, whose two sides are marked with the corresponding observables (color or court), to allow the basis choice.

of binary numbers and randomly chooses an encoding basis (color or court) for each bit. She prepares the QC in the chosen state and places it in an envelope that conceals its configuration (fig. 1(C)). The card is then sent to Bob, who randomly selects an observable to measure (which side of the card to look at). Then, he pulls half of the card from the envelope, mimicking quantum measurement collapse. After exchanging few cards, it becomes evident that, on average, Bob measures the observable matching Alice's preparation only half of the time. In the second step, Alice and Bob communicate over a public channel to disclose their preparation and measurement bases. This allows them to identify the correct key —composed of bits prepared and measured in the same basis— without directly revealing the results. The activity also demonstrates the impossibility of eavesdropping by introducing a third player (Eve). Depending on the audience, the no-cloning theorem —which ensures eavesdropper detection— can also be discussed at this stage. The exercise highlights how the protocol security relies on fundamental quantum principles, such as superposition and non-commutativity.

4. – The quantum walk activity

This activity illustrates a specific quantum algorithm: the discrete-time quantum walk [6]. It demonstrates how controlling the evolution of a quantum state can produce outcomes that differ fundamentally from their classical equivalents. The comparison is drawn between a classical random walk —exemplified by the "drunkard's walk", which yields a Gaussian distribution of positions— and the quantum walk, which generates a markedly different distribution with high-probability tails, enabling faster information propagation.

To explain how a quantum walker evolves and leads to the distribution shown in fig. 2(A), we designed an activity involving groups of four participants. Each group, collectively, corresponds to a single photon initially prepared in the "red" state (*i.e.*,

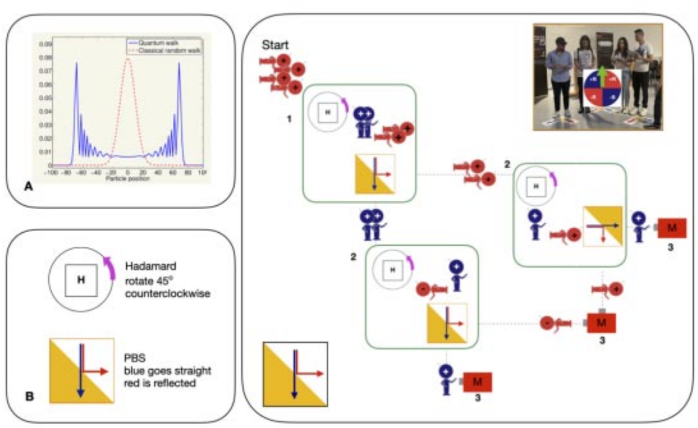

Fig. 2. – Description of the quantum walk activity. (A) Evolution of a quantum walk (continuous blue line) compared to a classical random walk (dashed red line), (B) diagram of the Hadamard gate and polarizing beam splitter. (C) Experimental setup. The colors, orientations and signs of the stick figures represent the state of the group after each step of the quantum walk before the measurement M.

horizontal polarization) entering a quantum maze. Each step of the walk is modeled using two elements: first, a 45° anti-clockwise rotator H (corresponding to the Hadamard gate), followed by a polarizing beam splitter (PBS). Each participant is equipped with a wheel that visually represents their part of the photon quantum state. At each step, they rotate the arrow on the wheel according to predefined instructions (see fig. 2(B)). After two steps, each one consisting of an H/PBS pair, two participants find themselves in the +blue state, localized on opposite sides of the walk. Each of them has a 50% probability of being measured at their position. Meanwhile, the two participants who reach the central spot from opposite paths are characterized by red components with opposite phases (plus-red and minus-red), resulting in destructive interference that cancels each other out. This activity proves effective in illustrating at least three key quantum concepts: 1) That it is possible to control the quantum evolution of a system to obtain outcomes radically different from the classical case; 2) that, as discussed in Feynman's experiment, a single photon can interfere with itself; 3) that the probabilistic nature of quantum mechanics manifests only at the moment of measurement, while the evolution itself is deterministic.

5. – Conclusions

Integrating "gaming" activities proved to be a crucial factor in the success of our educational approach, fostering curiosity and bringing abstract concepts to life. Through interactive tools like the Quantum Cards, participants grappled with non-commuting observables and the BB84 protocol not as passive observers, but as active players in a cryptographic challenge. The quantum walk activity transformed groups of participants into a single photon, making superposition, interference, and measurement collapse tangible through collaborative role-play. The power of these activities lies in their ability to mirror the weirdness of quantum mechanics while grounding it in intuitive experiences. Indeed, this approach has received the highest level of public appreciation according to our survey results.

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