Quantum Theory, Objectification and Some Memories of Giovanni Morchio

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More than twenty-two years have passed by since, as a young student at the Physics Department at the University of Pisa, I met Giovanni Morchio (1948-2021) for the first time. After taking his courses in 'Mathematical Methods of Physics' and 'Quantum Mechanics', from 2000 to 2002 I have worked with him on a degree thesis entitled: 'The Problem of Objectification in Quantum Theory: the Case of Pyramidal Molecules' (Sciortino, 2002). Even after so much time, some of his statements, expressed during our research meetings, still flash through my mind from time to time. They are short, almost lapidary sentences, expressed in a very colloquial language, yet logically rigorous and dense of meaning, which have generated reflections, produced ideas and suggested ways of approaching problems throughout all my intellectual life, sometimes even in my research work in philosophy of science and in my activity as a science writer. I consider the ability of Gianni (as friends called him) to be present in a person's mind and to fertilize it as the rare gift of a few teachers as well as of the great masters of thought.

One of the main goals of this chapter is to explore Gianni's approach to scientific problems and his ideas regarding certain conceptual issues that arise in quantum mechanics. I will pursue this goal by retracing the main stages of my research experience with him and by highlighting some personal memories. In so doing, I hope to achieve another non-secondary goal: to offer some glimpses of Gianni's combination of human qualities that has contributed to earning him great esteem and admiration among friends and colleagues. Before starting to work on my thesis, I had become passionate about the controversies surrounding the interpretation of quantum mechanics. These debates began around 1926, when Max Born (1882-1970) put forward the statistical interpretation of the theory's formalism, constructed between 1924 and 1926 by Erwin Schrödinger (1887-1961) and Werner Heisenberg (1901-1976). Eventually, most physicists agreed on an interpretation that can be traced back to the Copenhagen school and is called the 'probabilistic interpretation of quantum mechanics'. However, a smaller number of physicists attempted to reformulate quantum mechanics as a classical theory trying to demonstrate that the formalism was incomplete and that the probabilities were 'epistemic', i.e. they reflected our lack of knowledge, as happens in classical physics. What aroused my interest was the fact that this disagreement was rooted in some fundamental epistemological questions: do atomic objects exist independently of our observations? Is it possible to correctly understand their behavior? Can formalism incorporate philosophical biases into its structure? Indeed,

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Heisenberg wrote that 'all the opponents of the Copenhagen interpretation all agree on one point. It would, in their view, be desirable to return to the reality concept of classical physics or, to use a more general philosophic term, to the ontology of materialism. They would prefer to come back to the idea of an objective real world whose smallest parts exist objectively in the same sense as stones or trees exist, independently of whether or not we observe them' (Heisenberg, 1971 [1958], p. 115).

In their lectures, many teachers preferred to avoid these conceptual problems by focusing on the technical aspects of the formalism. Gianni, on the other hand, did not seem to shy away from these questions. If anything, he would delightedly discuss the ideas on quantum theory of the great minds of scientific and philosophical thought of the twentieth century. In his course called 'Quantum Mechanics' I had learned that the works of John Von Neumann (1903-1957), Simon Kochen (1934-), Ernst Specker (1920-2011) and John Bell (1928-1990) provide constraints to the possibility of a 'classical' reformulation of quantum mechanics (von Neumann, 1955) (Kochen & Specker, 1967) (Bell, 1966). In particular, a global probabilistic interpretation is not possible, i.e. an interpretation such that there exists a measure and a common space in which to represent the collection of all possible observations as functions and whose points assign a defined value to each variable (D'Espagnat, 1971) (Mermin, 1993). However, alongside these answers, many questions regarding the possibility of obtaining the interpretation of quantum mechanics from weaker hypotheses still remained unsolved. It was necessary to better understand on which assumptions the probabilistic interpretation of quantum mechanics was based and whether or not these assumptions could be inferred from the formalism.

When I asked Gianni to supervise my thesis on these issues, to my surprise, he suggested that I take a course in the history of physics. Indeed, he considered history, among other things, as an extremely important subject for understanding the true nature of scientific theories. Afterwards, the first preliminary discussions with him convinced me even more that a crucial question concerned what is called 'the problem of objectification'. Gianni had an original way of formulating this problem: 'it seems that the formalism of quantum mechanics does not to contain the facts, which must be assumed', he would say laughing, as he did when he was aware of the depth of a statement. I reflected on that concise sentence for some time, then I realized that the problem of objectification, as formulated by Gianni, could be rephrased in these terms: in order to obtain the current interpretation of quantum theory, the *fact* that a result of a measurement has been achieved (for example through a very precise position of a display pointer of the equipment) must be *assumed*. In other words, given the difficulty of deducing from the time evolution the empirical fact that a display pointer indicates a very precise result following a measurement, everything seems to suggest that the formalism of quantum mechanics never represents the notion of fact or event. That is, it seems that the current interpretation of quantum theory needs *a hypothesis of objectification*, i.e. an ontological assumption that consists in assuming the reality of facts or events such as, for example, having obtained a precise value in a measurement.

But, is it really so? Gianni and I wanted to question this general conclusion. What we wished was to find cases in which it was possible to remove the hypothesis of objectification. In other words, we wanted to suggest reasons for removing or, at least, weakening that assumption. The central aim of the thesis became to ask whether the hypothesis of objectification, which is currently added to the formalism, is not, at least in one case, deducible from it and in particular from the dynamics of the temporal evolution. The case study we were looking for had to: 1) represent a situation similar to that in which a macroscopic system such as a measurement apparatus, following interaction with a system, assumes a well-defined state (which or for example represents the fact that the result of a measurement is a particular value), i.e becomes objective 2) represent a fact in nature in which it is not clear whether its explanation can be derived from the formalism of quantum mechanics or whether a hypothesis of objectification is necessary for its explanation. Proving that such a fact can be deduced from the time evolution of quantum mechanics would have allowed us to conclude that there are cases in which the hypothesis of objectification is superfluous or, in other words, obtainable from the formalism.

With these ideas in mind, after an exploratory phase in which we inspected a number of examples which seemed particularly illuminating, we selected the case of chiral molecules of the type XH3 as our case study. For these molecules, the Schrödinger equation predicts that the two lowest-energy stationary states of the nucleus X are symmetric or antisymmetric under reflection with respect to the plane of the hydrogens. These states can be seen as superposition of localized states which, in fact, correspond to molecules with different chemical properties. In this case, one may ask whether quantum mechanics is compatible with the existence of molecules of one type or another. It was important to find an answer to this question because not only can a molecule of this kind be a good prototype of systems that are never observed in states of superposition (measurement apparatuses, pointers and macroscopic systems tout court), but it also has marked analogies with macroscopic systems. What we wanted to do was to schematize this selected case study in order to demonstrate that it is possible to deduce from the Schrödinger time evolution of a quantum-mechanical system, defined in the formalism, that typically certain chiral molecules of the type XH3 exhibit only localized states. This result would have allowed us to conclude that there exist situations in nature for which the formalism of quantum theory implies that a particular physical system, despite having delocalized superposition states, assumes well-defined and localized states, in a certain sense similar to those of a display pointer.

At that point the objectives of the thesis were much clearer and my work, under his supervision, began with an attempt to present an exposition of the probabilistic interpretation of quantum mechanics. This was supposed to be the content of the first part of my dissertation. I wanted to accomplish this task by putting myself in the best perspective to identify and expose the critical points of this interpretation. Gianni was very generous with his time right from the start, as many students acknowledge. He allowed me to call him at home in the evening, at around half past nine, when I needed help. And once a week, in his office, I would discuss the work done with him. I have many memories of that period. For example, one thing that impressed me was this: during discussions in his office on matters that were sometimes extremely technical and complicated, while we were in the process of working something out mathematically, the phone would ring. He would answer and speak for several minutes. At the end of the phone call, he would resume speaking from the exact point he had stopped, as if no one had ever interrupted him. His ability to refocus his attention on a particular task was impressive. Anyone would have had a hard time picking up again so quickly, after the phone call, the thread of the reasoning.

If there is one thing Gianni helped me with at that stage of my work, it was in making me understand the importance of distinguishing between physical formalism and its interpretation. 'A theory?' - he said once smiling - ' it is a heap of symbols, some rules and an interpretation'. What he wanted me to notice was the fact that, unlike in classical physics, where it is intuitive to represent the position of a planet as a vector of Euclidean space, in quantum mechanics the empirical meaning of the symbols is not immediately intuitive -- there is a clear split between mathematical entities and the objects they represent. As a consequence, the relationship between the symbols of quantum theory and the language we use to describe experiments is a priori problematic. Chris Isham has well expressed this point by saying that 'in classical physics, the "realist" and "instrumentalist" views of science fit together seamlessly, whereas in quantum physics they differ sharply, especially in their attitudes towards the idea of physical properties. That such a distinction can arise at all is closely tied to the different mathematical structures employed in the formulations of classical and quantum physics' (Isham, 1995, p. 3).

On the basis of these considerations, my exposition of the interpretation of quantum theory proceeded through these steps: 1) I distinguished two languages, on the one hand an 'observational language' with which we describe the experiments, and on the other hand a 'theoretical language', which includes the mathematical entities of quantum mechanics and classical physics; 2) I defined within this scheme what to interpret a 'symbolic language' means (the probabilistic interpretation of quantum mechanics associates propositions of the observational language with the terms of the quantum theoretical language); 3) I clarified, using the two previous points, the differences that exist, in the constitutive substance, between the classical and the quantum language; 4) I defined in terms of points 1) and 2) the postulates of the interpretation of the theoretical language of classical physics and of the probabilistic interpretation of the theoretical language of quantum mechanics.

The idea of distinguishing and analyzing two languages, the theoretical language, which contains the mathematical entities of classical physics and quantum mechanics, and the observational language, which is used to communicate the experimental results, was suggested to me by reading the works of proponents of logical positivism such as Rudolf Carnap (1891-1970) and Hans Reichenbach (1891-1953) who, together with other philosophers of science from Vienna in the first half of the 1900s, reflected on the problems raised by the crisis of classical physics and the birth of quantum mechanics. However, it was the conversations with Gianni that convinced me of the need for an analysis of the two formalisms and of the very meaning of interpretation. According to Gianni, the set of problems of the interpretation of quantum mechanics still required a work of reformulation which had necessarily to deal with problems of linguistic nature. In his mind, the interpretation of quantum mechanics could be better understood if one first comprehended how its theoretical language has been constructed, from what needs it has emerged and why it has that particular structure. A view of this kind, which considers the problem of language central to science, can be traced back to Wittgenstein. Not surprisingly, the *Tractatus Logico-Philosophicus* (1974 [1921]) was once the subject of our conversations. I still remember that, commenting on the statement 1.1 of Wittgenstein in that work, ' The world is the totality of facts, not of things' (Wittgenstein, 1974 [1921]), Gianni said: ' You see... what is taken for granted in philosophy, i.e. the claim that there are facts, is under discussion in physics'.

After providing the general characteristics of the observational and the theoretical language, I was able to explain that the formalism of classical physics has a very close relationship with the observational language by making clear that it is possible to identify the logical structure of the statements concerning a physical system with the structure of Boolean algebra of the subsets of a topological space that defines that system. I then discussed classical probability and stated the postulate that defines its interpretation. Afterwards, I explained that, when the topological spaces of classical physics are replaced with Hilbert spaces, then the logical structure of the observational statements acquires the property that in the classical case it acquired from the Boolean algebra structure of the subsets of a topological space. There is a profound link between statements that can be connected through logical connectives and the commutativity of the operators. At that point I introduced the postulate that interprets the notion of commutativity in quantum mechanics. Starting only from a class of states and operators in a Hilbert space, it is possible to associate a measure with certain functionals. In particular, the measurement of an interval can be interpreted as an output frequency of particular results of measurements performed on a collection of systems prepared in the same way.

The situation of classical physics is satisfactory: its theoretical language can be extended to the description of apparatuses which in a measurement process were first described by the observational language; moreover, it contains its interpretation of frequency, in the sense that there are sequences of points whose frequencies of visit of the intervals are equal to the measure μ of these. For reasons analogous to those of the classic case, the interpretation of the measure μ of an interval in terms of relative frequency implies that in every single measure of a set of systems all prepared in the same way a fact occurs. What we made clear is that it was not clear whether the nature of the theoretical language of quantum mechanics makes it possible the construction of a factual model to conclude that it implies an assumption of objectification. Due to the non-commutative structure of the theoretical language of quantum mechanics, the construction of a Bernoulli system is observably dependent. From the quantum description of the measurement process it is not possible to obtain the idea that an event has occurred, for example the fact that the measuring apparatus indicates a definite value. At first sight it seemed that one had to resign oneself to the idea that the theoretical language of quantum mechanics predicts the facts and that the hypothesis of objectification is always necessary. But, at this point, we asked ourselves whether the phenomenon of the localization of certain pyramidal molecules is a case in which the Schrödinger evolution implies the occurrence of an event and does not require an external objectification hypothesis.

The chirality of a molecule can be considered to all intents and purposes a fact described by the observational language. In our analysis, the problems of chirality were problems of localization since the chirality of a molecule corresponds to the localization of the wave function of its component nuclei. It must be noted, though, that chiral molecules of type XY3 are not necessarily chiral: in a multidimensional standard model for these molecules, the atom X is subject to a double-well potential and the Schrödinger equation has symmetric and antisymmetric eigenstates under reflection of the atom X with respect to the Y3 plane. In particular, the ground state and the first excited state are represented, respectively, by a symmetric and an antisymmetric wave function. These wave functions can be superimposed to give rise to two particular wave functions called 'right' and 'left', which are respectively located at the left and right side of the x axis and which correspond to two localized configurations of the molecule. Among pyramidal molecules, ammonia exhibits configurations that are not localized and the difference in energy between the ground and the first excited state can be obtained by spectroscopic measurements. However, if the nitrogen atom is replaced by heavier atoms, such as phosphorus or arsenic, to form arsine and phosphine, then such molecules exhibit localized patterns.

In the language of Hilbert spaces, the problem is to explain whether, due to the effect of time evolution, a system that has a space C^2 available 'chooses' two localized states defined by 'special directions', which correspond to the location of the molecule. Since chirality is a fact describable by observational language and since it can be reduced to localization, the property of a system of being in a localized state is a fact, in the same way as a pointer of an apparatus pointing in a certain direction. In this sense, the problem of chiral molecules, reduced to the simplest problem which consists in asking whether, due to the effect of time evolution, a system always finds itself in two precise states of a dimensional space and not in their superpositions, is a good prototype of the general objectification problem.

To explain the localization of molecules heavier than ammonia we took into consideration two significant physical facts: first, the times of electromagnetic transition from a localized state to the fundamental state are much greater than the times an atom X takes to oscillate from side to side of the plane of the atoms Y; second, contrary to ammonia, for heavy molecules such as arsine and phosphine, these times are much greater than the formation time of a molecule and the observation time. Hence we conjectured that the reason why arsine and phosphine exhibit localized configurations is that during the formation of these molecules the trivalent atom ends up in a localized state, resulting in, for times which are long compared to our times of observation, a localized configuration of the molecule.

Thus, the question we asked ourselves is whether, due to the effect of time evolution, at a time $t_0 << t << \tau$, where τ is the transition time and t_0 is the molecule formation time, the atom X is in a localized state. To address this question, we first wrote the one-dimensional Hamiltonian of a non-relativistic quantum particle interacting with the electromagnetic field and subjected to the force field of the atoms Y. This Hamiltonian consists of: the sum of the particle's kinetic energy and the potential due to the Y atoms (a symmetric double well potential, according to our assumption); a term that represents the interaction energy between the particle and the magnetic field, expressed through the creation and annihilation operators; finally, a term representing the energy of the radiation field, also expressed by means of the creation and annihilation operators.

On the basis of the experimental data on pyramidal molecules, we hypothesized that the ω gap between a level relative to an even eigenstate and to an odd eigenstate is very small compared to all the energies involved, a hypothesis which allowed us to state that $\tau >> t_0$. We showed that as the potential barrier V tends to infinity, the ω gap tends to zero; then we proved two essential points for what followed: the first consists in the fact that the right-hand state, superposition of the even ground state and the first excited odd state, has norm L^1 to the left of zero which is of the order of ω; the second consists in the fact that the eigenstates of the continuum of the Hamiltonian H_0, which represent an incoming wave from the left, have upper limit on the positive x axis of the order of ω. Afterwards, we defined the initial state of the particle and we showed that the formation time t_0 of the molecule can be identified with the passage time through the plane of the atoms Y of the wave packet describing the atom X.

The term representing the interaction energy in the Hamiltonian of our problem has been considered as a perturbation. I showed how the time evolution operation expands perturbatively in the interaction representation, I described the Hilbert space of the problem and I introduced the scheme and the notations necessary to calculate the amplitudes of the evolved state at first order of the Hamiltonian of the perturbing interaction in the basis product between the symmetric states and the one-photon Fock states. Our goal was now to establish the phase relationships between the amplitudes of the vector resulting from the time evolution, at time $t_0 << t << \frac{1}{\omega}$, of the initial state in the aforementioned basis. According to our conjectures, for times t such that $t_0 << t << \frac{1}{\omega}$, i.e. for times in which the packet 'has finished interacting' but which are still less than the oscillation times, the atom arriving from the left will end up in a left state. For times of the order of $\frac{1}{\omega}$, the oscillations between right and left will take place as predicted by quantum mechanics. From a mathematical point of view, we expressed this conjecture by making these points: the first is the fact that for $t \gg t_0$ the state evolved at time t has 'almost reached' its limit and can be replaced by its limit vector (up to errors in the ratio between t and t_0); the second is that, in Schrödinger's representation, for times t such that $t_0 \ll t \ll \frac{1}{\omega}$, this vector has phase differences of the order of ωt_0 between the amplitudes in the product basis obtained by taking the symmetric and antisymmetric states and the one-photon Fock states; and, for times of the order of $\frac{1}{\omega}$, it oscillates between a right and a left state. In order to prove these two points I estimated some expressions involving the amplitudes of the evolved vector at time t. I calculated these amplitudes explicitly and discussed the properties of the functions that compose them, then I calculated their punctual limit as t tends to infinity and I estimated the difference between the amplitudes at time t and their punctual limit in terms of $\frac{t_0}{t}$. Finally, I estimated the differences between the amplitudes showing that the state is localized. Given the observed values of ω, our model was inapplicable for ammonia molecules and we could not conclude that they are in localized states. However, or model was applicable for pyramidal molecules heavier than ammonia such as arsine and phosphine: the fact that these molecules exhibit localized states can be explained by referring to the dynamics of their formation. We therefore concluded that Schrödinger's temporal evolution implies, in a simple case, the transition from 'potentiality to actuality' without requiring a principle of objectification external to the theory.

After my graduation, I visited Gianni several times in his office. I recall with pleasure several conversations on the most disparate topics, including some on popular science books such as *The Road to Reality* (2004) by Roger Penrose and *A Brief History of Time* (1988) by Stephen Hawking. Commenting on the latter's popular science works, Gianni said, half-jokingly, that they tended to 'wrap some scientific problems in mysteries'. My view is that Gianni believed that scientific dissemination must be done in a clear and rigorous way. Where this is not possible, then it is better to give up: for example, according to him, the problems of quantum mechanics were so connected with the interpretation of his formalism that in some cases they could not be clearly expressed in the ordinary language.

The content of those conversations as well as some points made in my thesis have been of fundamental importance for my subsequent work (Sciortino, 2023). However, after the beginning my doctorate studies in the United Kingdom, I have had only sporadic meetings with him. The best memory I have of that period is this: I had to write a popular article on quantum mechanics for a magazine aimed at the general public. He gave me some valuable advice but, when I asked him if I could quote him in the article, he replied that he preferred not to be quoted: 'in my life I follow the maxim attributed to Epicurus: Λάθε βιώσας' – he answered smiling. With that maxim, which means 'live hidden', he alluded to that kind of life based on genuine values and away from the spotlight, as it is suggested in the 14th of Epicurus' 'sovran maxims', as collected by Diogenes Laertius (Diogene Laerzio, 1987, p. 1297). I believe that, beyond his outstanding scientific works, the most important thing Gianni has left us is his example of a life 'well lived', mindful of others and focused on what is authentic and meaningful.

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