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The Modal-Hamiltonian Interpretation: Measurement, Invariance, and Ontology

OLIMPIA LOMBARDI

2.1 Introduction

In the seventies, Bas van Fraassen (1972, 1974) proposed an approach to quantum mechanics different than those of the best known interpretations. According to him, although the quantum state always evolves unitarily (with no collapse), it is a *modal* element of the theory: It describes not what *is* the case but what *may be* the case. This idea led several authors since the eighties to propose the so-called *modal interpretations* (Kochen 1985, Dieks 1988, 1989, Vermaas and Dieks 1995, Dieks and Vermaas 1998, Bacciagaluppi and Dickson 1999, Bene and Dieks 2002), that is, realist, noncollapse interpretations of the standard formalism of quantum mechanics, according to which the quantum state assigns probabilities to the possible values of all the properties of the system. But since the contextuality of quantum mechanics (Kochen and Specker 1967) implies that it is not possible to consistently assign definite values to all the properties of a quantum system at a single time, it is necessary to pick out, from the set of all observables of a quantum system the subset of definite-valued properties. The different modal interpretations differ from each other mainly with respect to their rule of definite-value ascription (see Lombardi and Dieks 2017 and references therein).

Like most interpretations of quantum mechanics, the traditional modal interpretations were specifically designed to solve the measurement problem. In fact, they successfully reached this goal in the case of ideal measurements. However, a series of articles of the nineties (Albert and Loewer 1990, 1991, 1993, Elby 1993, Ruetsche 1995) showed that those traditional approaches based on the modal views did not pick out the right properties for the apparatus in nonideal measurements, that is, in measurements that do not introduce a perfect correlation between the possible states of the measured system and the possible states of the measuring apparatus. As ideal measurements can never be achieved in practice, this shortcoming was considered a “silver bullet” for killing modal interpretations (Harvey Brown, cited in Bacciagaluppi and Hemmo 1996). This explains the decline of the interest in modal interpretations since the end of the nineties.

What was not sufficiently noticed in the nineties was the fact that the difficulties of those original modal interpretations to deal with nonideal measurements was due not to their modal nature, but to the fact that their rule of definite-value ascription made the set of definite-valued observables to depend on the instantaneous state of the system. An author who did notice this was Jeffrey Bub, whose preference for Bohmian mechanics in those days can be understood in this context. In fact, if Bohmian mechanics is conceived as a member of the modal family whose definite-valued observables are defined by the position observable (Bub 1997), it turns out to be a natural alternative given the difficulties of the original modal interpretations.

Bub showed that the shortcomings of the original modal interpretations can be overcome by making the rule of definite-value ascription independent of the system's state and only dependent on an observable of the system. This was certainly an important step. Nevertheless, it was not sufficient to rehabilitate modal interpretations in the eyes of most philosophers of physics. What was not realized at that time is that position is not the only observable that can be appealed to in order to define the state-independent rule of definite-value ascription of a modal interpretation. It is in this point that the modal-Hamiltonian interpretation (MHI; Castagnino and Lombardi 2008, Lombardi and Castagnino 2008) entered the scene: The MHI endows the Hamiltonian of the quantum system with the role of selecting its definite-valued observables. With this strategy, it not only solves the problems of the original modal interpretations, but can also be successfully applied to many physical situations. However, perhaps due to the shadow of doubt that still covers the entire modal interpretation project, the MHI did not receive a serious attention by the community of the philosophers of physics. The present chapter intends to contribute toward modifying this situation by introducing the MHI in a conceptually clear and concise way, stressing its advantages both for facing the traditional interpretive problems of quantum mechanics and for supplying a physically meaningful account of relevant aspects of the theory.

For this purpose, the chapter is organized as follows. In Section 2.2, the two main interpretive postulates of the MHI will be introduced, emphasizing the role played by the Hamiltonian in them. In Section 2.3, the measurement problem is addressed from the MHI perspective; in particular, it will be argued that, beyond the formal von Neumann model, quantum measurement is a symmetry-breaking process that renders empirically accessible an otherwise inaccessible observable of the system. Section 2.4 will be devoted to assessing the MHI from the viewpoint of the invariances of the theory, in particular, of the

Galilei group. Finally, in Section 2.5, the ontological picture suggested by the MHI will be described, stressing how that picture supplies a conceptually clear solution to some traditional interpretive problems of quantum mechanics.

2.2 The Modal-Hamiltonian Interpretation

In this section, we shall introduce the MHI without discussing its advantages over other proposals. The arguments in its favor will become clear in the following sections, where we will argue for its physical relevance and we will apply it to solve some traditional interpretive challenges.

By adopting an algebraic perspective, the MHI defines a quantum system S as a pair $(\mathcal{O}, H)$ such that (i) $\mathcal{O}$ is a space of self-adjoint operators representing the observables of the system, (ii) $H \in \mathcal{O}$ is the time-independent Hamiltonian of the system S, and (iii) if $\rho_0 \in \mathcal{O}'$ (where $\mathcal{O}'$ is the dual space of $\mathcal{O}$) is the initial state of S, it evolves according to the Schrödinger equation. Here we will assume that the space $\mathcal{O}$ is a C*-algebra, which can be represented in terms of a Hilbert space $\mathcal{H}$ (Gelfand-Naimark-Segal [GNS] theorem). In this particular case, $\mathcal{O} = \mathcal{O}'$ and, therefore, $\mathcal{O}$ and $\mathcal{O}'$ are represented by $\mathcal{H} \otimes \mathcal{H}$. Nevertheless, $\mathcal{O}$ may be a different *-algebra, under the necessary conditions for its representation.

In this algebraic framework, the observables that constitute the quantum system are the basic elements of the theory, and the states are secondary elements, defined in terms of the basic ones. The adoption of an algebraic perspective is not a merely formal decision. As we will see in Section 2.5, when the logical priority of observables over states is transferred to the ontological domain, the space of observables turns out to embody the representation of the elemental items of the ontology, and this has relevant interpretive consequences.

A quantum system so defined can be decomposed into parts in many ways; however, not any decomposition will lead to parts which are, in turn, quantum systems. The expression "tensor product structure" (TPS) is used to call any partition of a closed system S, represented in the Hilbert space $\mathcal{H} = \mathcal{H}_A \otimes \mathcal{H}_B$, into parts S_A and S_B represented in $\mathcal{H}_A$ and $\mathcal{H}_B$, respectively. Quantum systems admit a variety of TPSs, each one leading to a different entanglement between their parts. However, there is a particular TPS that is invariant under time evolution: The TPS is *dynamically invariant* when there is no interaction between the parts (Harshman and Wickramasekara 2007a, b). In other words, in the dynamically invariant case the components' behaviors are dynamically independent from each other; each one evolves unitarily according to the Schrödinger equation. On this basis, according to the MHI, a quantum system can be split into subsystems when there is no interaction among the subsystems.

Composite systems postulate: A quantum system $S: (\mathcal{O}, H)$, with initial state $\rho_0 \in \mathcal{O}'$, is *composite* when it can be partitioned into two quantum systems $S^1: (\mathcal{O}^1, H^1)$ and $S^2: (\mathcal{O}^2, H^2)$, such that (i) $\mathcal{O} = \mathcal{O}^1 \otimes \mathcal{O}^2$ and (ii) $H = H^1 \otimes I^2 + I^1 \otimes H^2$ (where I^1 and I^2 are the identity operators in the corresponding tensor product spaces). In this case, we say that S^1 and S^2 are *subsystems* of the composite system $S = S^1 + S^2$. If the system is not composite, it is *elemental*.

With respect to the definite-valued observables, the basic idea of the MHI is that the Hamiltonian of the system, with its own symmetries, defines the subset of the observables that acquire definite actual values. The group of the transformations that leave the Hamiltonian invariant is usually called *Schrödinger group* (Tinkham 1964). In turn, each symmetry of the Hamiltonian leads to an energy degeneracy. The degeneracies with origin in symmetries are called “normal” or “systematic,” and those that have no obvious origin in symmetries are called “accidental” (Cohen-Tannoudji, Diu, and Lalöe 1977). However, a deeper study usually shows either that the accidental degeneracy is not exact or else that a hidden symmetry in the Hamiltonian can be found that explains the degeneracy. For example, the degeneracy in the hydrogen atom of states of different angular momentum l but the same principal quantum number n arises from a four-dimensional rotational symmetry of the Hamiltonian in momentum space (Fock 1935). For this reason it is assumed that once all the symmetries of the Hamiltonian have been considered, a basis for the Hilbert space of the system is obtained and the “good quantum numbers” are well defined.

Once these symmetry considerations are taken into account, the basic idea of the MHI can be expressed by the classical Latin maxim *Ubi lex non distinguit, nec nos distinguere debemus* (where the law does not distinguish, neither ought we to distinguish). The Hamiltonian of the system, with its symmetries, is what determines which observables acquire definite values. This means that any observable whose eigenvalues would distinguish among eigenvectors corresponding to a single degenerate eigenvalue of the Hamiltonian does not acquire definite value, because such an acquisition would introduce in the system an asymmetry not contained in the Hamiltonian. Once this idea is understood, the rule of definite-value ascription can be formulated in a very simple way:

Actualization rule: Given an elemental quantum system $S: (\mathcal{O}, H)$, the actual definite-valued observables of S are H, and all the observables commuting with H and having, at least, the same symmetries as H.

The justification for selecting the Hamiltonian as the preferred observable ultimately lies in the physical relevance of the MHI and in its ability to solve interpretive difficulties. These issues will be the content of the following sections.

2.3 The Modal-Hamiltonian View of Quantum Measurement

2.3.1 Measurement and Correlations

In general, the quantum measurement problem is presented in terms of the von Neumann model, without framing it in the context of the measurement practices. But the purpose of a quantum measurement is not to discover the preexisting value of a system's observable, but to reconstruct, at least partially, the state of the measured system. Therefore, the following distinction is in order:

- *Single measurement*: It is a single process, in which the reading of the pointer is registered. A single measurement, considered in isolation, does not yet supply relevant information about the state of a measured system.
- *Frequency measurement*: It is a repetition of identical single measurements, whose purpose is to obtain the certain coefficients of the measured system's state on the basis of the frequencies of the pointer readings in many single measurements.

A frequency measurement supplies relevant information about the state of the system, but is not yet sufficient to completely identify such a state. In order to reconstruct the state of the measured system it is necessary to perform a collection of frequency measurements with different experimental arrangements.

The von Neumann model addresses the quantum measurement problem in the framework of the single measurement. This is completely reasonable to the extent that, if we do not have an adequate explanation of the single case, we cannot account for the results obtained by the repetition of single cases. Nevertheless, it should not be forgotten that a single measurement is always an element of a measurement procedure by means of which, finally, frequencies are to be obtained.

Let us begin, then, by the single measurement. If, as in the original modal interpretations, the rule of definite-value ascription depends on the instantaneous state of the system, it is not surprising that it does not supply the expected result in nonideal measurements: When the state of the composite system measured system+apparatus does not introduce a perfect correlation between the eigenstates of the measured system's observable and the eigenstates of the apparatus' pointer, it is not difficult to see that the pointer will not belong to the context of definite-valued observables. By contrast, if the rule of definite-value ascription does not depend on the instantaneous state of the system, this problem does not arise. It can be proved that the MHI explains the definite value of the measurement apparatus' observable both in the ideal and in the nonideal single measurements (for a formal demonstration and physical examples, see Lombardi and Castagnino 2008: section 6; for the account of consecutive measurements, see Ardenghi, Lombardi, and Narvaja 2013).

While definite records of the apparatus' pointer are obtained even in nonideal situations, one can legitimately ask whether all nonideal measurements are equally unsatisfactory. The MHI supplies a clear criterion to distinguish between *reliable* and *nonreliable* frequency measurements (for a detailed explanation and applications, see Lombardi and Castagnino 2008: section 6). In the former case, the coefficients of the measured system's state can be computed on the basis of the frequencies of the pointer's readings is spite of the imperfect correlation; in the latter case, the same computation would give inaccurate results (for a presentation of the reliability criterion in informational terms, see Lombardi, Fortin, and López 2015). Albert and Loewer (1990, 1993) were right in claiming that the ideal measurement is a situation that can never be achieved in practice: The interaction between measured system and measurement apparatus never introduces a completely perfect correlation; in spite of this, physicists usually perform successful measurements. The MHI account of the quantum measurement shows that perfect correlation is not a necessary condition for "good" measurements: The coefficients of the system's state at the beginning of the process can be approximately obtained even when the correlation is not perfect, if the reliability condition is satisfied. Nevertheless, both in the reliable and in the nonreliable case, a definite reading of the apparatus' pointer is obtained in each single measurement.

2.3.2 Measurement and Symmetries

In the von Neumann model of a single measurement, the observable A of the measured system S, whose eigenstates will be correlated with those of the pointer P, is considered in formal terms and deprived of any physical content. Then, the interaction between S and the measuring apparatus M is only endowed with the role of introducing the correlation between A and P. However, the analysis of physical situations of measurement shows that there are further aspects to be considered beyond correlations.

Let us consider the free hydrogen atom, characterized by the Coulombic interaction between nucleus and electron. Since the Hamiltonian is degenerate due to its space-rotation invariance, the hydrogen atom is described in terms of the basis $\{|n, l, m_l\rangle\}$ defined by the complete set of commuting observables (CSCO) $\{H, L^2, L_z\}$. Nevertheless, that space-rotation invariance makes the selection of L_z a completely arbitrary decision: Given that space is isotropic, we can choose L_x or L_y to obtain an equally legitimate description of the free atom. The arbitrariness in the selection of the z-direction is manifested in spectroscopy by the fact that the spectral lines of the free hydrogen atom give no experimental evidence about the values of L_z: We have no empirical access to the number m_l of the free atom. The MHI agrees with those experimental results, because it does not assign a definite value to L_z; the definite value of L_z would break the symmetry of the Hamiltonian of the free hydrogen atom in a completely arbitrary way.

If we want to have empirical access to L_z, we need to apply a magnetic field B along the z-axis, which breaks the isotropy of space and, as a consequence, the space-rotation symmetry of the atom's Hamiltonian. In this case, the symmetry breaking removes the energy degeneracy in m_l: Now L_z is not arbitrarily chosen but selected by the direction of the magnetic field. However this, in turn, implies that the atom is no longer free: The Hamiltonian of the new system includes the magnetic interaction. As a consequence, the original degeneracy of the $(2l+1)$-fold multiplet of fixed n and l is now removed, and the energy levels turn out to be displaced by an amount $\Delta\omega_{nlm_l}$, which is also function of m_l: This is the manifestation of the so-called Zeeman effect. This means that the Hamiltonian, with eigenvalues ω_{nlm_l}, is now nondegenerate: It constitutes by itself the CSCO $\{H\}$ that defines the preferred basis $\{|n, l, m_l\rangle\}$. According to the MHI's rule of definite-value ascription, in this case H and all the observables commuting with H are definite-valued: Since this is the case for L^2 and L_z, in the physical conditions leading to the Zeeman effect, both observables acquire definite values.

Besides the free hydrogen atom and the Zeeman effect, the MHI was applied to many other physical situations, leading to the results expected from a physical viewpoint; e.g., the free-particle with spin, the harmonic oscillator, the fine structure of atoms, the Born-Oppenheimer approximation (see Lombardi and Castagnino 2008: section 5). Recently, the interpretation was applied to solve the problem of optical isomerism (Fortin, Lombardi, and Martínez González 2018), which is considered one of the deepest problems for the foundations of molecular chemistry.

All those physical situations show that we have no empirical access to the observables that are generators of the symmetries of the system's Hamiltonian; and, in the context of measurement, the observable A of the measured system S may be one of those observables. This is also the case in the Stern–Gerlach experiment, where S_z is a generator of the space-rotation symmetry of $H_{spin} = kS^2$; it is the interaction with the magnetic field $B = B_z$ that breaks the isotropy of space by privileging the z-direction and, as a consequence, breaks the space-rotation symmetry of H_{spin}. Therefore, when the observable A to be measured is a generator of a symmetry of the Hamiltonian of S, the interaction with the apparatus M must not only establish a correlation between A and the pointer P, but also must break that symmetry. Therefore, from a physical viewpoint, measurement can be conceived as a process that breaks the symmetries of the Hamiltonian of the system to be measured and, in this way, turns an otherwise nondefinite-valued observable into a definite-valued and empirically accessible observable. This means that the formal von Neumann model of quantum measurement must be complemented by a physical model, in terms of which, measurement is a symmetry breaking process that renders a symmetry generator of the system's Hamiltonian empirically accessible.

2.4 The Modal-Hamiltonian Interpretation and the Role of Symmetries

2.4.1 The MHI and the Galilei Group

In contrast with the great interest of physicists in the symmetries of physical theories, the discussion on this topic has been scarce in the field of quantum mechanics (Lévi-Leblond 1974). This situation is reflected in the field of the interpretation of the theory, where the relevance of the Galilei group – the symmetry group of nonrelativistic quantum mechanics – is rarely discussed in the impressive amount of literature on the subject. This is a serious shortcoming in the foundational context, because the fact that a theory is invariant under a group does not guarantee the same property for its interpretations, to the extent that, in general, they add interpretive assumptions to its formal structure. The MHI, on the contrary, addresses the issue of the role and meaning of the Galilei transformations in the interpretation: the study of whether and under what conditions the MHI satisfies the physical constraints imposed by the Galilei group leads to interesting consequences.

As it is well known, the invariance of the fundamental law of a theory under its symmetry group implies that the behavior of the system is not altered by the application of the transformation: In terms of the passive interpretation of symmetries, the original and the transformed reference frames are equivalent. In the particular case of nonrelativistic quantum mechanics, the application of a Galilei transformation does not introduce a modification in the physical situation, but only expresses a change of the perspective from which the system is described.

Harvey Brown, Mauricio Suárez, and Guido Bacciagaluppi (1998) correctly pointed out that any interpretation that selects the set of the definite-valued observables of a quantum system is committed to explaining how that set is transformed under the Galilei group. This question is particularly pressing for realist interpretations of quantum mechanics, which conceive a definite-valued observable as a physical property that objectively acquires an actual definite value among all its possible values: The actualization of one of the possible values has to be an objective fact. Therefore, to the extent that the theory preserves its invariance under the Galilei group, the set of the definite-valued observables of a system should be left invariant by the Galilei transformations. From a realist viewpoint, it would be unacceptable that such a set changed as the mere result of a change in the perspective from which the system is described. The MHI meets the challenge and overcomes it successfully. In fact, it can be proved that, in the situations in which the Schrödinger equation remains invariant under the group, the set of definite-valued observables picked out by the modal-Hamiltonian rule of definite-value ascription also remains invariant (see Ardenghi, Castagnino, and Lombardi 2009, Lombardi, Castagnino, and Ardenghi 2010).

However the argument can also be developed in the opposite direction. Instead of starting by the interpretation and considering its behavior under the transformations of the relevant group, one can begin by the group of symmetry and ask for the constraints that it imposes on interpretation. In the case of nonrelativistic quantum mechanics, the objectivity of the definite-valued observables must be preserved by making them invariant under the Galilei group. The natural way to reach this goal is to appeal to the *Casimir operators of the Galilei group*, which by definition are the operators invariant under all the transformations of the Galilei group. If the interpretation has to select a Galilei-invariant set of definite-valued observables, the members of such a set must be the Casimir operators of the group or functions of them. The central extension of the Galilei group has three Casimir operators which, as such, commute with all the generators of the group: They are the mass operator M, the squared-spin operator S^2, and the internal energy operator $W = H - P^2/2mW$. The eigenvalues of the Casimir operators label the irreducible representations of the group; so, in each irreducible representation, the Casimir operators are multiples of the identity: $M = mI$, where m is the mass; $S^2 = s(s+1)I$, where s is the eigenvalue of the spin S; and $W = wI$, where w is the scalar internal energy.

This result, which places the Casimir operators of the group in the center of the stage, may seem to disagree with an interpretation such as the MHI, which endows the Hamiltonian with the leading role. The definite-valuedness of the mass operator M and the squared-spin operator S^2 are compatible with the MHI rule of definite-value ascription, because both commute with H and do not break its symmetries (they are multiples of the identity). But the Hamiltonian is not a Casimir operator of the Galilei group; the Casimir operator is the internal energy. Nevertheless, the disagreement is only apparent. The Hamiltonian is the sum of the internal energy and the kinetic energy of the system. But the kinetic energy can be disregarded: When the system is described in a reference frame at rest with respect to its center of mass, then the kinetic energy turns out to be zero and the Hamiltonian is identified with the internal energy. This means that the internal energy is the magnitude that carries the physically meaningful structure of the energy spectrum, whereas the kinetic energy represents an energy shift that is physically nonrelevant and merely relative to the reference frame used for the description.

Summing up, the modal-Hamiltonian interpretation can be reformulated in an explicitly invariant form, according to which the definite-valued observables of a quantum system are (i) the observables C_i represented by the Casimir operators of the Galilei group in the corresponding irreducible representation, and (ii) all the observables commuting with the C_i and having, at least, the same symmetries as the C_i (Lombardi, Castagnino, and Ardenghi 2010). Therefore, the interpretation should be more precisely referred to by the name "modal-Casimir interpretation," although in the case of nonrelativistic quantum mechanics the original name is also adequate.

2.4.2 Interpretation and Symmetry

Now we can come back to the question about the constraints that the Galilei group imposes on the interpretation of quantum mechanics, but now independently of the MHI. Let us recall that the application of a transformation belonging to the symmetry group of a theory does not introduce a modification in the physical situation, but only expresses a change of the perspective from which the system is described. This leads to the natural idea, expressed by a wide spectrum of authors (e.g., Minkowski 1923, Weyl 1952, Auyang 1995, Nozick 2001), that the invariance under the relevant group is a mark of objectivity.

On the other hand, as a consequence of the Kochen-Specker theorem (1967), it is necessary to pick out, from the set of all observables of a quantum system, the subset of observables that may have definite values. In turn, from a realist viewpoint, the fact that certain observables acquire an actual definite value is an objective fact in the behavior of the system; therefore, the set of definite-valued observables selected by a realist interpretation must be also Galilei-invariant. But the Galilei-invariant observables are always functions of the Casimir operators of the Galilei group. As a consequence, one is led to the conclusion that any realist interpretation that intends to preserve the objectivity of the set of the definite-valued observables may not stand very far from the MHI (Lombardi and Fortin 2015).

The invariance of the Schrödinger equation holds for the case of isolated systems, that is, in the case that there are no external fields applied on the system. Since, in nonrelativistic physics, fields are not quantized, the effect of external fields on the system has to be accounted for by its Hamiltonian: The potentials have to modify the form of the Hamiltonian because it is the only observable involved in the time-evolution law. As a consequence, in the presence of external fields, the Hamiltonian is no longer the generator of time-displacements; it only retains its role as the generator of the dynamical evolution (see Laue 1996, Ballentine 1998). In turn, since the Hamiltonian includes the action of the fields, the result of the action of the Galilei transformation on it must be computed in each case, and the Galilei invariance of the Schrödinger equation can no longer be guaranteed. This fact suggests the possibility of generalizing the idea of relying on symmetry groups in two senses.

It cannot be expected that relativistic quantum mechanics be invariant under the Galilei group, given the fact that it includes the action of electric and magnetic fields described by a theory that is not Galilei invariant, but Poincaré invariant. In turn, in quantum field theory, fields are quantum items, not external fields acting on a quantum system; as a consequence, the generators of the Poincaré group do not need to be reinterpreted in the presence of external factors. These facts lead to generalize the group-based interpretive ideas: The realist interpretation, expressed in terms of the Casimir operators of the Galilean group in nonrelativistic quantum mechanics, can be transferred to the relativistic domain by changing the symmetry group accordingly – the definite-valued observables of a system in relativistic quantum mechanics and in quantum field theory would be those represented by the Casimir operators of the Poincaré group. Since the mass operator M and the squared-spin operator S^2 are the only Casimir operators of the Poincaré group, they would always be definite-valued observables. This conclusion agrees with a usual physical assumption: Elemental particles always have definite values of mass and spin, and those values are precisely what define their different kinds. Moreover, the classical limit of relativistic theories manifests the limit of the corresponding Casimir operators (see Ardenghi, Castagnino, and Lombardi 2011): There is a meaningful limiting relation between the observables that acquire definite values according to relativistic theories and those that acquire definite values according to nonrelativistic quantum mechanics.

These group-based interpretive ideas can be further generalized in a second sense. If invariance is a mark of objectivity, there is no reason to focus only on spacetime global symmetries. Internal or gauge symmetries should also be considered as relevant in the definition of objectivity and, as a consequence, in the identification of the definite-valued observables of the system. For instance, in relativistic quantum mechanics a gauge symmetry is what identifies the charge as an objective quantity. Therefore, a realist interpretation can be extended to the gauge symmetries of the theory: The observables represented by operators invariant under those symmetries are also definite-valued observables according to the theory.

In summary, besides its wide applicability in the nonrelativistic quantum domain, the MHI opens the way for a general interpretive strategy, valid for any realistic view of quantum theories – the definite-valued observables of a system, whose behavior is governed by a certain theory, are the observables invariant under all the transformations corresponding to the symmetries of the theory, both external and internal.

2.5 A Modal Ontology of Properties

2.5.1 The Structure of the Ontology

Traditionally, the interpretations of quantum mechanics concentrate their efforts on the interpretive challenges of the theory. For instance, they focus on searching a solution of the measurement problem without falling beyond the limitations imposed by the no-go quantum theorems. Due to their difficulty, these tasks usually lead people to disregard ontological issues, in particular, the questions about the nature of the items referred to by quantum mechanics. The MHI has tackled the ontological questions from the very beginning.

As explained in Section 2.2, the MHI adopts an algebraic perspective. This decision about the formalism is not confined to the formal domain, but rather has relevant consequences about the structure of the ontology referred to by quantum mechanics, in particular, about the *basic categories* of such an ontology. In fact, when the logical priority of observables over states is transferred to the ontological domain, the space of observables turns out to embody the representation of the elemental items of the ontology – observables (mathematically represented by self-adjoint operators) ontologically represent *type-properties*, and the values of the observables (mathematically represented by the eigenvalues of the corresponding operators) ontologically represent the *possible case-properties* corresponding to those type-properties. Among the possible case-properties of a type-property, only one acquires a definite value (Lombardi and Castagnino 2008: section 8).

In this modal ontology of properties, a quantum system is a bundle of properties: type-properties with their corresponding case-properties. The notion of bundle of properties is a well-known idea in contemporary metaphysics: Philosophers of the empiricist tradition have preferred to replace the traditional picture of properties "stuck" to an underlying and unobservable substance by an ontological realm where individuals are nothing but *bundles of properties*. Properties have metaphysical priority over individuals; therefore, they are the fundamental items of the ontology. However, the view of bundles of properties that is appropriate for quantum mechanics does not agree with the "bundle theory" of twentieth-century analytic metaphysics concerning two aspects.

In the first place, according to the traditional versions of the bundle theory, an individual is the confluence of certain case-properties, under the assumption that the corresponding type-properties are all determined in terms of actual definite values. For instance, a particular ball is the confluence of a definite position, say, on the chair; a definite shape, say, round; a definite color, say, white; etc. The ball is the bundle of those actual case-properties. In general, bundle theories identify individuals with bundles of *actual* properties. By contrast, in the framework of the MHI, a system is identified by its space of observables, which defines all the admissible type-properties with their corresponding possible case-properties. Therefore, a quantum system is *a bundle of possible case-properties*; it inhabits the realm of possibility and manifests itself only partially in the realm of actuality.

This ontological interpretation embodies a possibilist conception of possibility, as opposed to an actualist view, which reduces possibility to actuality. According to *possibilism*, possibility is an ontologically irreducible feature of reality. Possible items – *possibilia* – constitute a basic ontological category (see Menzel 2007). In other words, possibility is a way in which reality manifests itself, a way independent of and not less real than actuality. The reality of possibilia is manifested by the fact that they may produce definite effects on actual reality even if they never become actual (e.g., "non-interacting experiments" of Elitzur and Vaidman 1993, Vaidman 1994).

The second specific aspect of this quantum-bundle view is related to the way in which bundles are conceived. In the traditional versions of the bundle theory, the claim is that individuals are bundles of properties; therefore, it is necessary to find what confers individuality to individuals. In general, the task is fulfilled by some subset of the bundle's properties, together with some further principle that ensures that no other individual must possess that subset and that preserves the identity of the individual through change. By contrast, due to the indistinguishability of "identical particles," quantum mechanics poses a serious challenge to the notion of individual, either in the substratum-properties picture or in the bundle picture (see French and Krause 2006 and references therein). The identification of the complexions resulting from the permutations of identical particles makes the notion of individual run into trouble.

The MHI tackles the problem by endorsing the idea that quantum systems are not individuals – they are strictly bundles, and there is no principle that permits them to be subsumed under the ontological category of individual. Regrettably, this ontological picture is not properly captured by any formal theory whose elemental symbols are variables of individual. An ontology populated by bundles of possible properties cries for a "logics of predicates," in the spirit of the "calculus of relations" proposed by Alfred Tarski (1941), where individual variables are absent.

2.5.2 *One Ontology, Many Solutions*

Quantum mechanics poses different ontological problems – contextuality prevents the simultaneous assignment of determinate values to all the properties of the system, nonseparability seems to undermine the independent existence of noninteracting systems, and indistinguishability challenges the traditional category of individual. The usual strategies focus only on one of these problems: They design an interpretation to solve it, disregarding the remaining difficulties. With its ontology of possible properties, the MHI aspires to provide a "global" approach, which solves most problems in terms of a single ontology.

The Kochen-Specker theorem expresses the impossibility of ascribing actual case-properties to all the type-properties of the system in a noncontradictory manner. The classical idea of a bundle of *actual* properties does not work in the quantum ontology. But this is not a difficulty for the MHI, which conceives the quantum system as the bundle of all the *possible* type-properties with their corresponding case-properties, as defined by the space of observables. This ontological view is immune to the challenge represented by the Kochen-Specker theorem, because this theorem imposes no restriction on possibilities (see da Costa, Lombardi, and Lastiri 2013).

Quantum nonseparability is the consequence of the nonfactorization of entangled states. When the states are assigned to individual systems that interacted in the past, the difficulty is to explain the correlations between the values of observables belonging to noninteracting systems, which typically are separated in space. The assumption of collapse leads to understand nonseparability as nonlocality, at risk of falling into the "spooky action at a distance" reported by Albert Einstein. Without collapse, nonseparability seems to imply a kind of holism, in the sense that quantum systems are not composed by what are commonly conceived as their subsystems; but this idea can hardly be compatibilized with the view of systems as individuals, that is, entities that preserve their identity through change. For the MHI, the interpretation of nonseparability as holism does not represent a difficulty. Since quantum systems are strictly bundles and not individuals, there is no principle of individuality that preserves the individuality of the component systems in the composite system (see da Costa and Lombardi 2014). The composite system is a single bundle, where the identity of the components is not retained. Therefore, the new bundle-system acts and reacts as a whole – there are not subsystems whose state nonseparability must be explained or whose correlations seem to imply instantaneous action at a distance.

The same idea of the "dissolution" of component bundles in the composite bundle is what allows the MHI to face the problem of indistinguishability. In the discussions about the indistinguishability of "identical particles," the problem is usually formulated in terms of the possible combinations (complexions) that can be obtained in the distribution of particles over possible states. The problem is, then, to explain why a permutation of particles does not lead to different complexions in quantum statistics. This feature is introduced in the formalism as a restriction on nonsymmetric states, but the strategy has an unavoidable ad hoc flavor in the context of the theory. According to the MHI ontology, when a bundle is the result of the combination of identical bundles, it can be expected that the result does not depend on the order in which the original identical bundles are considered; the combination of identical bundles must be commutative. This commutativity is manifested by the fact that the observables that constitute the resulting bundle-system are represented by operators symmetric with respect to the permutation of the indices coming from the original identical bundles. Here symmetry is not an ad hoc assumption but a consequence of an ontological feature. When the expectation values of these symmetric observables are computed, only the symmetric part of the state has an effect. The nonsymmetric part is superfluous, because it plays no role in the physically measurable magnitudes (see details in da Costa et al. 2013). Therefore, symmetrization is not the result of an ad hoc strategy, but is due to ontological reasons: The symmetry properties of states are a consequence of the symmetry of the observables of the whole composite system, which is, in turn, a consequence of the ontological picture supplied by the interpretation. In other words, from the perspective given by the modal-Hamiltonian interpretation, indistinguishability is not a relation between particles manifested in statistics, but rather an *internal symmetry* of a single bundle of properties.

In summary, according to the MHI, the talk of individual entities and their interactions can be retained only in a metaphorical sense. In fact, even the number of particles is represented by an observable, and superpositions of different particle numbers are theoretically possible. This fact, puzzling from an ontology populated by individuals, involves no mystery in an ontology of properties: If quantum systems are bundles of possible properties, the particle picture, with a definite number of particles, is only a contextual picture valid exclusively when the number of particles satisfies the constraints of the rule of definite-value ascription. In other cases, wave packets may remain narrow and more or less localized during a relatively long time. In this way, particle-like behavior can temporarily emerge – wave packets can represent approximately definite positions and can follow an approximately definite trajectory (see Lombardi and Dieks 2016). Moreover, the MHI has proved to be compatible with the theory of decoherence (Lombardi 2010, Lombardi, Ardenghi, Fortin, and Castagnino 2011, Lombardi, Ardenghi, Fortin, and Narvaja 2011). Nevertheless, those particular situations do not undermine the fact that quantum systems are nonindividual bundles of properties.

2.6 Conclusions and Perspectives

The MHI has been developed and successfully articulated in many directions since its first presentation in 2008. Of course, this does not mean that any interpretive question about quantum mechanics has already been solved. Nevertheless, given the results obtained up to this moment, it deserves to be taken into account and further explored.

There are several issues that can still be faced from this interpretive framework. A very interesting question is that related to the interpretation of external fields in a theory that, as quantum mechanics, does not treat fields as quantized entities. In particular, the Aharonov-Bohm effect is worthy of being analyzed from an ontology-of-properties view. Another topic to be examined is how the MHI is in resonance with a closed-system view of decoherence (Castagnino and Lombardi 2004, 2005a, b, Castagnino, Laura, and Lombardi 2007, Castagnino, Fortin, and Lombardi 2010, 2014), according to which decoherence is a process relative to the selected partition of a closed system and how this leads to a top-down view of quantum mechanics based on an algebraic view that turns entanglement and discord also into relative phenomena (for initial ideas, see Lombardi, Fortin, and Castagnino 2012, Fortin and Lombardi 2014, Lombardi and Fortin 2016). Finally, the natural subsequent interpretive step consists in extending the MHI to quantum field theory, not only regarding the definite-valued observables, but also with respect to the ontology referred to by the theory. In particular, an ontology-of-properties view seems to favor a field view in the debate on fields vs. particles, but without representing an obstacle to explaining the emergence of the nonrelativistic quantum ontology. These different problems will guide the future research on the further development and extrapolation of the MHI.

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