Statistical-Realism versus Wave-Realism in the Foundations of Quantum Mechanics

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Abstract: Different realistic attitudes towards wavefunctions and quantum states are as old as quantum theory itself. Recently Pusey, Barret and Rudolph (PBR) on the one hand, and Auletta and Tarozzi (AT) on the other, have proposed new interesting arguments in favor of a broad realistic interpretation of quantum mechanics that can be considered the modern heir to some views held by the fathers of quantum theory. In this paper we give a new and detailed presentation of such arguments, propose a new taxonomy of different realistic positions in the foundations of quantum mechanics and assess the scope, within this new taxonomy, of these realistic arguments.

1 Introduction

In a recent paper Pusey, Barret and Rudolph[1] (2011) propose a new and strong argument against a statistical interpretation of quantum states. They claim that if quantum mechanical predictions are correct then distinct quantum states must correspond to distinct physical states of reality. This result has been hailed as a seismic[2] result in the foundations of quantum mechanics and probably the most important result since Bell's theorem. It is indeed the single most popular result in the foundations of quantum mechanics in recent years. However, whether it actually has the scope it has been claimed to have, still needs to be assessed. In this paper we explore such a question. In particular we argue that PBR offers a (probably) decisive argument against a particular interpretation of quantum mechanics that is broadly realistic in spirit. However we argue that not only are broadly anti-realistic interpretations left untouched by the argument but also that other realistic options remain open. We then present a new and significantly different version of a neglected argument, first proposed by Auletta and Tarozzi[3], which, if sound, would be able to rule out many more realistic interpretations than PBR. Thus we conclude that this argument, even if weaker, is wider in scope than PBR. The plan of the paper is as follows. In section 2 we give a somewhat detailed reconstruction of the PBR result. In section 3 we give a new formulation of the original AT argument. We contend that both PBR and AT are broadly realistic arguments. We then propose in section 4 a

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[1] Hereafter PBR.

[2] *Nature*, 17th November 2011: http://www.nature.com/news/quantum-theorem-shakes-foundations-1.9392.

[3] AT from now on.

taxonomy of realistic positions in the interpretation of quantum mechanics. We arrive at a simple tree-model that allows us to assess, at least *prima facie*, the scope of different arguments in the foundations of quantum mechanics. To put it roughly the scope of an argument is related to its position in this simple tree-model. We contend that PBR and AT arguments occupy different places in our tree-model and thus, have different scopes. As is clear even from this brief introduction we are interested not in the technical details of the arguments but rather in their scope and logical position within the foundations of quantum mechanics. Section 5 is dedicated to a brief conclusion.

2 The PBR argument

The core of the PBR result is nicely summed up in the abstract of the paper. Let us quote it at length:

"There are at least two opposing schools of thought [on the interpretation of quantum states]. […] One is that a pure state is a physical property of the system, much like position and momentum in classical mechanics. Another is that even a pure state has only a statistical significance, akin to a probability distribution in statistical mechanics. Here we show that, given only very mild assumptions, the statistical interpretation of the quantum state is inconsistent with the predictions of quantum theory" (Pusey et al. 2011: 1)

They however devote just a few lines in the paper to spelling out rigorously and clearly the distinction between a statistical and a non statistical interpretation of a quantum state[4]. It is of crucial importance to understand clearly such a distinction in order to appreciate the scope of the argument. We will therefore firstly provide some simple definitions of statistical and non statistical quantum states. These definitions are driven by the analogies Pusey et al. themselves point out in the abstract and are in line with Harrigan and Spekkens (2007: 4-5) to which they refer.

Let λ be a complete specification of the properties of a system. We will refer to λ as the *ontological*[5] *state* of a system. Let Λ stand for the *ontological state space*. Suppose a particular state is prepared via preparation P. Then with every preparation we can associate a probability distribution $p(\lambda/P)$ over Λ. We do not require this distribution to be sharp. We refer to $p(\lambda/P)$ as the *epistemic state,* for it encodes the observer's knowledge about the system.

It is maybe worth recalling here the distinction between epistemic probabilities, i.e. probabilities understood as degrees of belief, and objective probabilities, such as relative frequencies. The probability $p(\lambda/P)$ is an example of the first kind of

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[4] Using a particular example of flipping a coin.

[5] The term "ontic" was introduced into modern philosophical language by Martin Heidegger, in order to grasp the notion of something before any contact with the knowing subject. Harrigan and Spekkens (2007) refer to λ as the "ontic state". On a more careful analysis it seems to us that the λ they introduce is a hypothesis of the subject, so we beileve the term "ontological" to be more appropriate.

probabilities, since it encodes our hypothesis about the properties of a system given a certain preparation method.

Pusey et al. claim that in a non statistical interpretation of a quantum state the ontological state is very much like the position and momentum of classical mechanics, i.e. a physical property of the system under consideration. Let y be a point particle of classical mechanics. Then its ontological state space is the set of all possible pairs (x, p) where x is the position and p the momentum of the particle. In classical mechanics the situation is fairly simple. Let S be the set of all classical states, i.e. the classical state space and let S_i denote the classical state of the particle y at time t_i. Then we simply have that $S_i = \lambda_i = (x_i, p_i)$, i.e. the classical state is simply identical to the ontological state. Also, we will have that the ontological state space is simply the particle's phase space. Therefore the classical state determines the ontological state. Moreover in this case then we trivially have that different classical states pick out distinct and disjoint regions of Λ. These consequences will guide us in formulating different yet equivalent definitions of what PBR calls a "physical quantum state", i.e. a non statistical state.

All is in order to provide different equivalent definitions of quantum states that are not statistical.

Let P_1 and P_2 be two preparations for a quantum system QS that assign to QS two different pure states $|\varphi_1\rangle$ and $|\varphi_2\rangle$ respectively. Then let us say that:

(1.1) (*Physical Quantum State*) $|\varphi_i\rangle$ is a physical quantum state iff $|\varphi_i\rangle$ uniquely determines λ, i.e. either $\lambda = (|\varphi_1\rangle, \omega_1)$ or $\lambda = (|\varphi_2\rangle, \omega_2)$, where ω_i represents possible supplementary hidden variables [6];

(1.2) (*Physical Quantum State*) $|\varphi_i\rangle$ is a physical quantum state iff for all λ, $p(\lambda/P_1) \, p \, (\lambda/P_2) = 0$.

Definition (1.2) informally says that the epistemic states associated with different preparation procedures, and hence with different pure states are non overlapping. In fact, if the joint probability $= 0$, it follows that at least one of them must have probability $= 0$. We have argued that these definitions are equivalent in the classical case. This equivalence carries over into the quantum domain. Note that both our terminology and our definition are consistent with PBR's use. They write in fact: "If the quantum state is a physical property of the system […] the quantum state is uniquely determined by λ" (Pusey et al. 2011: 1). We too have explicitly made an analogy with classical mechanics. Let us now turn to the statistical view then.

Here the analogy is, naturally enough, with statistical mechanics. Suppose S is a complex system, such as a gas, constituted by a collection of particles. The description of the state in terms of phase space trajectories is in principle possible. However it is usually the case that we cannot know the ontological states of all the

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[6] Harrigan and Spekkens (2007) calls the models in which there are hidden variables *supplemented* models.

particles that constitute the gas at a given time. Hence we cannot know which point of the phase space the system S exactly occupies at a given time. Usually we know only some of the thermodynamical properties of S, such as pressure and temperature. It is well known that this thermodynamical state is compatible with many different microscopic states, i.e. it is compatible with different $\lambda_i \in \Lambda$[7]. Then we assign a probability distribution over phase space which represents our ignorance about which point of the phase space is exactly occupied by S. Such a probability distribution is simply what we called an epistemic state. We have already pointed out that the probability distribution does not uniquely determine the ontological state of the system, that is to say a thermodynamical description fails to determine the complete list of the particles positions and momenta. Analogously to the previous case these facts taken together imply that the statistical state fails to determine uniquely the epistemic state, therefore two different statistical states do not pick out disjoint regions of the ontological space. Hence the joint probability of two distinct epistemic states $\neq 0$. This suggests the following definitions (2.1)-(2.2) that mirror definitions (1.1)-(1.2) above:

Let P_1 and P_2 be two preparations for a quantum system Q_S that assign to Q_S two different pure states $|\varphi_1\rangle$ and $|\varphi_2\rangle$ respectively. Then:

> (2.1) (*Statistical Quantum State*) $|\varphi_i\rangle$ is a statistical quantum state iff $|\varphi_i\rangle$ does not uniquely determine λ;

> (2.2) (*Statistical Quantum State*) $|\varphi_i\rangle$ is a statistical quantum state iff for some λ, $p(\lambda/P_1)$ p $(\lambda/P_2) \neq 0$

In this case, as Harrigan and Spekkens write, the quantum state "is not a variable in the ontic [ontological] state space at all, but rather encodes a probability distribution over the ontic [ontological] state space" (Harrigan and Spekkens, 2007: 4). In other words the quantum state is not a physical property of the quantum system but rather a description of the observer's knowledge of the system. Again, these definitions are perfectly consistent with Pusey et al. for they write: "If the quantum state is statistical in nature [...] then a full specification of λ need not determine the quantum state uniquely" (Pusey et al. 2011: 2). Note that also these definitions show clearly that physical states and statistical states are clearly exclusive notions [8].

Note that this kind of statistical interpretation is essentially different from the one proposed, for example, in Ballentine (1998). Ballentine (1998) argues that probabilities $p(k/\lambda,M)$ must be interpreted as relative frequencies concerning an

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[7] For a philosophically illuminating introduction to statistical mechanics and its relation to thermodynamics that highlights different points that are relevant to the present discussion see Albert (2003: 35-70), in particular pp. 38- 40. In Albert's words "any full specification of the *thermodynamic* situation of a gas necessarily falls very short of being a full specification of its *physical situation*, [...] *thermodynamic* situations invariably correspond to enormous collections of distinct *micro*situations" (Albert, 2003: 39, italics in the original) Note that by substituting epistemic state for thermodynamic situation and ontological state for physical situation/microsituation we arrive precisely at our characterization.

[8] Whether they are exhaustive notions as well is a substantive question.

ensemble of similar measurements, where k is the result of measurement M. Thus Ballentine (1998) is concerned not with the epistemic probabilities p(λ/P), but rather with objective ones. It is noteworthy that Harrigan and Spekkens (2007), after a careful investigation, maintain that Einstein's interpretation of quantum mechanics, had an epistemic, rather than an objective character.

Let us sum up what is at stake here. Assume that a quantum isolated system QS exemplifies a well defined set of physical properties[9] $\lambda = (O_1 \ldots O_n)$. A measurement is supposedly a procedure that reveals some of the Os. The question is: can QS be in different pure states? Or equivalently: could the system QS be prepared via two different preparation methods? If the quantum state is a statistical state the answer is yes to both, whereas if it is a physical state it is no. Here is another way to put it. Suppose two quantum isolated systems QS_1 and QS_2 are prepared via two different preparations that assign quantum pure states $|\varphi_1\rangle$ and $|\varphi_2\rangle$ respectively. QS_1 and QS_2 exemplifies the set of properties λ_1 and λ_2 respectively. Could it be that $\lambda_1 = \lambda_2$? If $|\varphi_1\rangle$ and $|\varphi_2\rangle$ are statistical states the answer is yes, whereas if they are physical states the answer is no.

Let us be even clearer and let us consider a more realistic example. Suppose an isolated quantum system QS exemplifies the following set of properties $\lambda = (\uparrow_x , O_2, O_3 \ldots O_n)$. What is QS pure quantum state?

If the statistical interpretation is right, i.e. quantum states are statistical states, it can be both[10] $|\varphi_1\rangle = |\uparrow_x\rangle$ and $|\varphi_2\rangle = |\uparrow_x\rangle + |\downarrow_x\rangle = |\uparrow_y\rangle$. This shows clearly that statistical states are not properties of QS since the very same set of properties is compatible with different pure states. Suppose now that $|\varphi_1\rangle$, $|\varphi_2\rangle$ are associated with the two preparation methods P_1 and P_2 respectively. It follows that the probability that QS exemplifies λ when prepared via P_1, i.e. p(λ/P_1), $\neq 0$. The same goes for p(λ/P_2), so that the conjoint probability p(λ/P_1) p(λ/P_2) $\neq 0$.

On the other hand, if the physical interpretation is right, i.e. quantum states are physical states, then every set of properties is compatible with only one pure quantum state, in our case $|\varphi_1\rangle = |\uparrow_x\rangle$. This shows that physical states are properties of QS. Moreover it follows that p(λ/P_2) = 0 so that the conjoint probability p(λ/P_1) p(λ/P_2) = 0.

The PBR result aims to prove that all quantum states are physical states. The argument is rather straightforward. They envisage a particular measurement and they show that it is impossible to recover the predictions of the quantum theory for the outcomes of that measurement if the particular quantum states involved are statistical states. Hence, either Quantum Mechanics is false or quantum states are physical properties of quantum systems. They explicitly admit that the argument rests upon the following assumptions, which we state almost *verbatim*:

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[9] O stands for observables.
[10] We neglect normalization constants.

(3) (*Pure State-Well Defined Properties Link*): If a quantum system *QS* is prepared in a pure state then it has a well defined set of physical properties;

(4) (*Possible Uncorrelated Systems*) It is possible to prepare different physical systems such that their physical properties are uncorrelated;

(5) (*Very Weak Locality*) If two quantum systems are such that their physical properties are uncorrelated, then the measuring devices respond solely to the physical properties of the systems they measure.

Note that (4) and (5) jointly claim that it is possible to prepare different non entangled quantum systems and that measurements on such systems depend solely on the system that is measured.

Now to the argument.

Let QS_1 be a quantum system that could be prepared in two different ways P_1 and P_2 such that quantum theory assigns to S_1 the two non orthogonal pure states $|\varphi_1\rangle_1$ and $|\varphi_2\rangle_1$ respectively. Suppose that actually $\langle\varphi_1|\varphi_2\rangle = 1 / \sqrt{2}$ and choose a basis for the two dimensional Hilbert space $\mathcal{H}_1$ such that $|\varphi_1\rangle_1 = |0\rangle_1$ and $|\varphi_2\rangle_1 = |+\rangle_1 = | (|0\rangle + |1\rangle) / \sqrt{2}$. By assumption (3) QS_1 exemplifies a well defined set of physical properties, let us call it λ_1. Now suppose that every quantum state is a statistical state. Hence, by definition (2.1) the quantum state does not uniquely determine λ_1, and λ_1 is compatible with both $|0\rangle_1$ and $|+\rangle_1$. Let us say that the probability of that happening is $p_0(1)$, $p_+(1)$ respectively. Hence it follows[11]:

(6) $p_0(1) \neq 0, p_+(1) \neq 0$

The argument in favor of 6 is straightforward. If either these probabilities are $= 0$ the joint probability will be 0 as well, i.e.:

(7) $p_0 (\lambda_1/P_1) p_+(\lambda_1/P_2) = 0$

And $|0\rangle_1$ and $|+\rangle_1$ will fail to meet definition (2.2).

Now, prepare a quantum system QS_2 in exactly the same way as QS_1 was prepared and such that these two systems are uncorrelated. This possibility is granted by assumption (4). QS_2 will exemplify the set of properties λ_2. Then repeat then the argument above to obtain:

(8) $p_0(2) \neq 0, p_+(2) \neq 0$

Claims (6) and (8) simply say that λ_1 is compatible with both $|0\rangle_1$ and $|+\rangle_1$ and that λ_2 is compatible with both $|0\rangle_2$ and $|+\rangle_2$. Consider now the joint system QS_1 and QS_2. Since each system is compatible with two quantum states, the joint system is compatible with any of the four tensor product states:

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[11] We do not require that either $p_0(1) = p_+(1)$ or that $p_0(1) \neq p_+ (1)$.

(9) (*Joint System 1*) $|J_1\rangle = |0\rangle_1 \otimes |0\rangle_2$

(*Joint System 2*) $|J_2\rangle = |0\rangle_1 \otimes |+\rangle_2$

(*Joint System 3*) $|J_3\rangle = |+\rangle_1 \otimes |0\rangle_2$

(*Joint System 4*) $|J_4\rangle = |+\rangle_1 \otimes |+\rangle_2$

By the same argument it follows that the probabilities of these occurrences are again all non zero, i.e.:

(10) $p_1(J_1) \neq 0 \quad p_2(J_2) \neq 0 \quad p_3(J_3) \neq 0 \quad p_4(J_4) \neq 0$

Now, QS_1 and QS_2 are brought together and measured. The joint state lives in a four-dimensional Hilbert space onto which such measurement projects and that can be spanned by the four orthogonal states:

(11) $|\xi_1\rangle = 1/\sqrt{2}(|0\rangle_1 \otimes |1\rangle_2 + |1\rangle_1 \otimes |0\rangle_2)$

$|\xi_2\rangle = 1/\sqrt{2}(|0\rangle_1 \otimes |-\rangle_2 + |1\rangle_1 \otimes |+\rangle_2)$

$|\xi_3\rangle = 1/\sqrt{2}(|+\rangle_1 \otimes |1\rangle_2 + |-\rangle_1 \otimes |0\rangle_2)$

$|\xi_4\rangle = 1/\sqrt{2}(|+\rangle_1 \otimes |-\rangle_2 + |-\rangle_1 \otimes |+\rangle_2)$

Where $|-\rangle = (|0\rangle_1 - |1\rangle_2)/\sqrt{2}$. Now we measure the compound system QS_1-QS_2 on the directions $|\xi_1\rangle$-$|\xi_4\rangle$. Given (5) the results of the measurement on the two systems are uncorrelated. It is easy to see that:

(12) $\langle J_1 | |\xi_1\rangle = 0 \quad \langle J_2 |\xi_2\rangle = 0 \quad \langle J_3|\xi_3\rangle = 0 \quad \langle J_4| \xi_4\rangle = 0,$

i.e. that for every possible measurement parameter there is a state of the joint system that is orthogonal to it. In this case quantum theory predicts that:

(13) $p_1(J_1) = 0 \quad p_2(J_2) = 0 \quad p_3(J_3) = 0 \quad p_4(J_4) = 0$

If the first, second, third or fourth measurement, an outcome is found, that clearly contradicts (10). That is for each $|\xi_i\rangle$ there is a parameter $|J_i\rangle$ such that at least one of the p_i is = 0. We have derived a contradiction assuming that the quantum states in question were statistical states according to definition (2.1)[12]. Hence we arrive at the following conclusion: either quantum predictions are falsified or "no physical state λ of the system can be compatible with both of the quantum states $|0\rangle$ and $|+\rangle$" (Pusey et al, 2011: 2)[13]. That is to say quantum states uniquely determine λ and thus physical

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[12] Strictly speaking in order to yield the desired conclusion the argument has to be generalized for any pair of quantum states. Pusey et al. show that this is possible only if we allow, given assumption (4), *n* uncorrelated systems to be prepared (Pusey et al. 2011: 3). They also go on to give a version of the argument that is robust against small amounts of experimental noise.

[13] We will arrive at a similar conclusion when dealing with AT argument.

properties of the system, very much like position and momentum in classical mechanics.

A brief discussion of the relevance of the result is in order. We believe it is most easily appreciated if one considers the measurement problem. The statistical interpretation does not face such a problem. Consider the following argument. Suppose a quantum system is in the superposition state $|\varphi_1\rangle = |\Uparrow_x\rangle + |\Downarrow_x\rangle$. If a spin measurement is performed the state collapses in one of the terms of the superposition, let us say $|\varphi_2\rangle = |\Uparrow_x\rangle$. If $|\varphi_1\rangle$ is a statistical state, it is not a property of the system. Hence the measurement has not changed its properties. The statistical state supposedly encodes our knowledge of the properties of the system. Thus a measurement represents simply a Bayesian updating of our knowledge. On the other hand if the physical interpretation is right, then quantum states $|\varphi_1\rangle$ and $|\varphi_2\rangle$ do represent different physical situations and the measurement is a physical process that does change the properties of the measured system and the measurement problem is a serious problem indeed. The PBR result forces us to face the full strength of such a problem.

It is worth noting that Pusey et al. consider their argument as an argument in favor of a broadly realistic stance in the foundation of quantum mechanics. It is then not mere coincidence that the paper opens with a brief discussion of different realistic and anti-realistic interpretations of quantum mechanics. The authors mention that the "quantum wave function was originally conceived by Schrödinger as a tangible, physical wave" (Pusey et al., 2011: 1), that many "have suggested that the quantum state should properly be viewed as something less than real" (Pusey et al., 2011: 1) and that some have gone as far as to "hold that quantum systems do not have physical properties or that the existence of quantum systems at all is a convenient fiction. In this case, the state vector is a mere calculational device" (Pusey et al., 2011: 1). And we have already pointed out that the PBR result is intended to show that the quantum state is a real physical property of a quantum system. Even from these few remarks it is possible to see that we are dealing with different antirealistic and realistic intimations. In the realistic camp, for example, Pusey et al. seem to understand the quantum state as a *property* of a quantum system, whereas Schrödinger's original position was rather that the wavefunction is an *individual*. We will attempt to provide a simple tree model to classify different realtistic and antirealistic interpretations of quantum mechanics in section 4. Before that let us present another broadly realistic argument, which, if sound, is closer to Schrödinger's original position.

3 The AT argument

In this section we present another broadly realistic argument. It is a significant variation and a development of the original argument in Auletta and Tarozzi (2004). Consider the following experimental set up (Fig. 1):
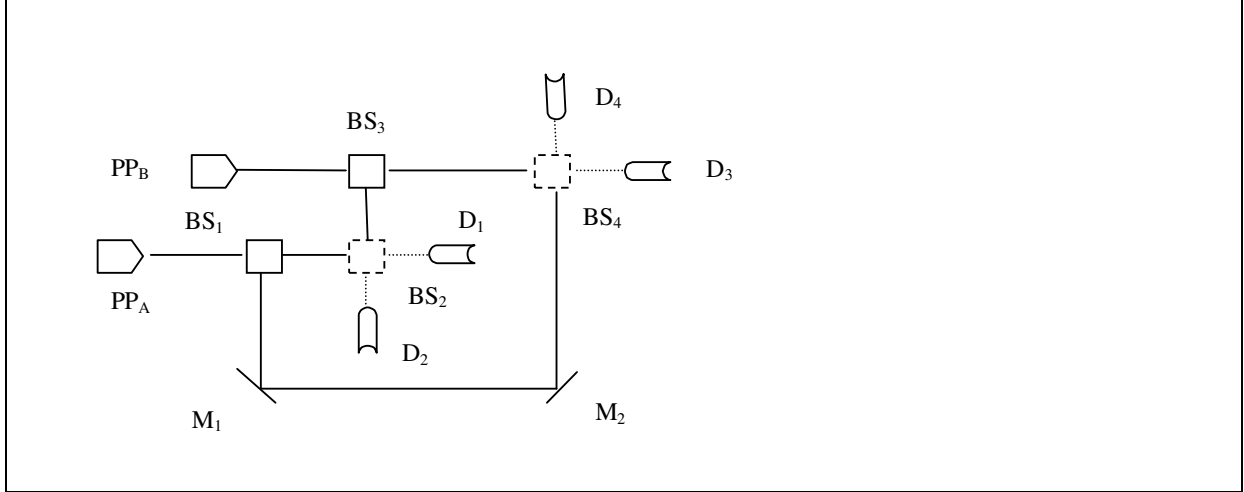
Two photonic pumps PP_A and PP_B pump two photons A, B in the same state, which we dub $|A\rangle$ and $|B\rangle$ respectively. Then the two beam splitters BS_1 and BS_3 split each photon into the "vertical components" $|A_v\rangle$, $|B_v\rangle$ and the "horizontal components" $|A_h\rangle$, $|B_h\rangle$ depending on the path taken by each component. These components are then recombined at the other two beam splitters BS_2 and BS_4. Behind these beam splitters there are four detectors labeled D_1-D_4. We will use the notation $|1_A\rangle$ to indicate the following state: "detector 1 has clicked because of the arrival of photon A". Thus in general such a state is indicated with $|n_K\rangle$ where n =1,…,4 and $K = A,B$. Different reflecting mirrors are placed in such a way as to accommodate the length of different paths as in Fig.1[14], detectors D_1,…, D_4 are perfect recording devices and beam splitters are taken to be symmetric.

Let us trace down the evolution of the system. At time t_1, before the two photons enter the beam splitters BS_1 and BS_3, the system will be simply in state Ψ_1 given by:

(14) $\Psi_1 = |A\rangle|B\rangle$

Then photons A and B enter the two beam splitters BS_3 and BS_1 respectively. After passing these beamsplitters, at t_2 their state will be respectively:

(15) $|A\rangle| \rightarrow \frac{1}{\sqrt{2}}(i|A_v\rangle + |A_h\rangle)$; $|B\rangle \rightarrow \frac{1}{\sqrt{2}}(i|B_v\rangle + |B_h\rangle)$

Where the imaginary coefficient i multiplies the quantum state whenever there is a reflection. Substituting (15) into (14) we have the total state Ψ_2 at t_2, i.e.:

(16) $\Psi_2 = \frac{1}{\sqrt{2}}(-|A_v\rangle|B_v\rangle + i|A_v\rangle|B_h\rangle + i|A_h\rangle|B_v\rangle - |A_h\rangle|B_h\rangle)$

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[14] The two paths from PP_A to BS_4 and from PP_B to BS_4 have the same length, even if it is not clear from the figure. This is done to allow interference.

Now, the vertical component of photon A and the horizontal component of photon B enter the beamsplitter BS_2. This will have an effect analogous to the one described by equation (15). It will yield:

$$(17)\ |A_v\rangle \rightarrow \frac{1}{\sqrt{2}}(|2_A\rangle + i|1_A\rangle)\ ;\ |B_h\rangle \rightarrow \frac{1}{\sqrt{2}}(i|2_B\rangle + |1_B\rangle)$$

Then the horizontal component of A and the vertical component of B enter the beamsplitter BS_4, determining a similar evolution:

$$(18)\ |A_h\rangle \rightarrow \frac{1}{\sqrt{2}}(|3_A\rangle + i|4_A\rangle)\ ;\ |B_v\rangle \rightarrow -\frac{1}{\sqrt{2}}(i|3_B\rangle + |4_B\rangle)$$

Equations (17) and (18) give us the state for both the vertical and horizontal components of photons A and B. We can then substitute them into equation (16) to obtain the final state Ψ_4 at t_4, where t_4 is the time in which one of detectors D_3, D_4 clicks, whereas t_3 indicates the time in which either D_1 or D_2 clicks. This final state is given by:

$$(19)\Psi_4 = \frac{1}{2\sqrt{2}}(|3_A\rangle|3_B\rangle - |4_A\rangle|4_B\rangle - |2_A\rangle|2_B\rangle -$$
$$|1_A\rangle|1_B\rangle + i(|2_A\rangle|3_B\rangle + |2_B\rangle|3_A\rangle + |1_A\rangle|4_B\rangle + |1_B\rangle|4_A\rangle))$$

Equation (19) gives us the first important information about the quantum evolution of the system. It in fact tells us that it is completely symmetric in the indices A and B, for in each term of (19) they both appear. Hence we can never distinguish which photon has arrived in which detector. Now, if we perform an adequate post-selection to discard the cases in which both photons are detected by the same detector, i.e.: the states $|n\rangle|n\rangle$ with $n = 1,\dots 4$, and after normalization we end up with:

$$(20)\ \Psi_{4ps} = \frac{1}{\sqrt{2}}\ (|2\rangle|3\rangle + |1\rangle|4\rangle),$$

where *ps* stands for post-selection state and we have discarded indices A and B for the symmetry reasons mentioned above. Now, state (20) is clearly reminiscent of the EPR state:

$$(21)\ |EPR\rangle = \frac{1}{\sqrt{2}}\ (|\uparrow\rangle|\downarrow\rangle - |\downarrow\rangle|\uparrow\rangle)$$

This analogy suggests a similar interpretation. In the EPR case we know that the total state spin of the system = 0 but, since the state is not separable we do not know which particle has either spin up or spin down. All we know is that they are perfectly anti-correlated, i.e. if a measurement yields spin up for the first particle we will find spin down for the other. The same holds for state (20). It is a non separable state. We have already argued that we do not know which detector has detected which photon but we do know that if the D_1 clicks then D_4 must as well. The same goes for D_2 and D_3.

Now, since we cannot establish which photon has been detected by which detector it is clear that we cannot reconstruct their path. If we take, as is usually the case, the

possibility of reconstructing spacetime trajectories as a necessary condition to display a particle-like behavior[15] we can conclude that this argument establishes the following conditional:

(22) Wavelike Behavior → Entanglement

Moreover it is possible to argue that in the case of a certain type of particle-like behavior there will be no detectors correlation, i.e. there is an argument for the opposite direction of the conditional. We argue by contraposition, i.e. we show that in the case of particle-like behavior you will not have detectors correlation. The first thing to do is to find a case in which photons entering the measurement set up of Fig.1 display such a behavior. We first show that there is a case in which it is possible to know which detector has detected which photon and that is possible to reconstruct their path. This should be evidence enough of particle-like behavior. Suppose you remove beamsplitter BS_4. Hence the horizontal component of A will surely end up in D_3 and the vertical component of B will surely end up in D_4, i.e. we will have the following quantum evolution:

(23) $|A_h\rangle \rightarrow |3_A\rangle$; $|B_v\rangle \rightarrow |4_B\rangle$

Now equations (17) and (23) give us each component of each photon. Substituting them in equation (16) we get the state Ψ_{3ps} at time t_3, where we have already post-selected the runs in which different detectors detect the photons:

(24) $\Psi_{3s} = \frac{1}{2\sqrt{2}}(|3_A\rangle|1_B\rangle + i|3_A\rangle|2_B\rangle - |2_A\rangle|4_B\rangle - i|1_A\rangle|4_B\rangle)$

Equation (24) tells us that if at time t_4 A clicks D_3 it is photon B that is detected at t_3 by either D_1 or D_2. The same goes if photon B clicks D_4 at t_4[16]. Note that A can never click D_4 nor B can click D_3. In this case then we can know which photon has been detected by which detector thus allowing us to reconstruct their path. Hence we have an example of particle-like behavior. It remains to be shown that in such a case there is no detector correlation. And this is immediately clear from equation (24) itself. Suppose D_1 clicks at t_3. We should then consider those terms of equation (24) in which $|1\rangle$ appears. These two terms contain both $|3_A\rangle$ and $|4_B\rangle$. This means that D_3 and D_4 have the same probability to click. The same goes if it is D_2 that clicks at t_3. And this in turn implies that in this case there is no detector correlation. Together with the argument in favor of (22) we are led to the following conclusion: wavelike behavior is both a necessary and sufficient condition for detectors correlation, i.e.:

(25) Wavelike Behavior ↔ Entanglement

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[15] Note that this seems to presuppose that "particle-like behavior" and "wave-like behavior" are mutually exclusive. We know however that the contraposition is gradual and not dichotomic. Since this complication does not affect the overall argument we will stick to this simpler version.

[16] Note that we could in principle insert BS_4 after t_3 but before t_4, as in Wheeler's (1978) "delayed choice" argument thus transforming the post-selected state (24) into (20). In this case we would create the entanglement *after* D_1 or D_2 have already clicked.

Now we have to evaluate the consequences of claim (25). In order to do so let us first consider a traditional Mach-Zender interferometer (Fig. 2) first.

PP produce photons at such a rate that a single photon passes through the interferometer at a time. As in the previous experimental set up M_1 and M_2 are two reflecting mirrors, BS_1 and BS_2 are two symmetric beamsplitters and D_1 and D_2 are perfect recording devices. There is indeed something new in the apparatus, namely the phase shifter PS. The first beamsplitter splits the photon into its vertical and horizontal components. The phase shifter PS is set in such a way that the angle between these two components = 0.
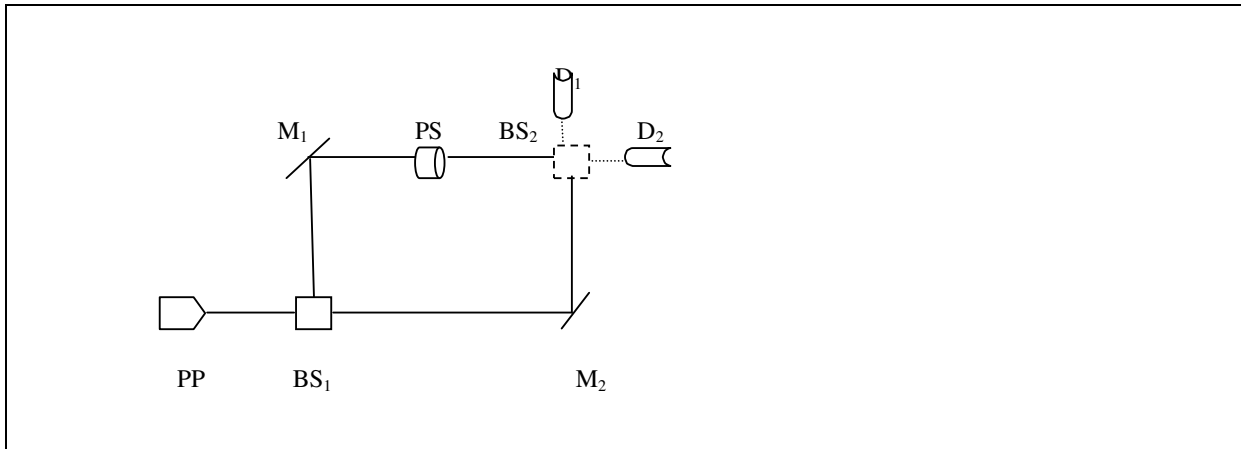

Fig. 2 The Mach-Zender Interfermoter

If so it turns out that there is interference in BS_2 and all of the photons are actually detected in D_1. Interference is indeed evidence of wavelike behavior. Moreover, as it is well known, any attempt to establish what happens between BS_1 and BS_2 cancels the interference phenomenon and half of the photons will be detected in D_1, the other half in D_2, as we would expect in the case that they were classical particles. This last argument has the same logical structure as the AT argument we have put forward. It allows a similar conclusion, i.e.:

(26) Wavelike Behavior $\leftrightarrow$ Interference

So, the Mach-Zender apparatus shows that wavelike behavior is both a sufficient and necessary condition for interference. AT suggests instead that wavelike behavior is necessary and sufficient for entanglement. Now, whereas interference is not a typical quantum phenomenon, entanglement is. We will return to this important point later on.

Consider now a general case of such a typical quantum phenomenon, namely entanglement. Let QS_1 and QS_2 be two quantum systems and consider a general observable O with two possible eigenfunctions A, B. In general the states of QS_1, QS_2 will be given by:

(27) $|1\rangle = f_1|A\rangle_1 + f_2|B\rangle_1$; $|2\rangle = g_1|A\rangle_2 + g_2|B\rangle_2$

In general the composite system QS_{12} is in a state described by a vector in the four-dimensional tensor product space $\mathcal{H}_{12} = \mathcal{H}_1 \otimes \mathcal{H}_2$, i.e.:

(28) $|12\rangle = c_1|A\rangle_1|A\rangle_2 + c_2|A\rangle_1|B\rangle_2 + c_3|B\rangle_1|A\rangle_2 + c_4|B\rangle_1|B\rangle_2$

Entangled states are such that c_1-c_4 are not functions of the *f*s and *g*s. Suppose now we take QS_1 and QS_2 far apart in space so that they will have both a definite spatial position and path. This is usually taken to be indicative of the fact that the systems in question can be interpreted as particles. This in turns implies that, in general, entanglement does not imply wavelike behavior.

Now, everything is in order, to give an accurate evaluation of claim (25) and of the scope of the AT argument in general.

The AT argument and its conclusion (25) shows that there are particular physical situations in which wavelike behavior plays a crucial role in accounting for a phenomenon such as entanglement that (i) is a typical quantum phenomenon and (ii) was previously thought to have no connection with wavelike behavior. Thus it acknowledges wavelike behaviors of micro-objects that had not been yet noticed.

The conclusion of the argument just proposed can be rephrased in a similar fashion to the PBR argument of section 2: either quantum mechanical predictions are false and we will have no correlations between detectors clicking when BS_4 is in place or we should attribute some sort of "ontological reality to the wave" (Auletta and Tarozzi, 2004: 89).

Auletta and Tarozzi give yet another argument in favor of a realistic interpretation, an argument that seems by parity of reasoning. They write: "it seems to us that there is no reason to attribute reality only to the particle and not to the wave, since both aspects give rise to different and complementary predictions" (Auletta and Tarozzi, 2004: 93).

At this point it is useful then to consider an objection to our main argument that mimics the classic objection raised against the violation of the Heisenberg's uncertainty principle in the case of a single slit experiment, as presented for example in Feynman (1964: I, 38-3, 38-4) and Popper (1982: 54). Recall our argument for the particle-like behavior of photons when beamsplitter BS_4 is removed. We were able to tell which photons clicked detectors D_1 or D_2 at t_3 only because we already knew which photon was detected by D_3 or D_4 at t_4, that is, we were able only to "retrodict" the identity of different photons. But cases of "retrodiction" could be considered physically irrelevant. This objection as it stands is quite controversial for it seems to suggest that scientific theories are just predictive instruments without descriptive power. In other words it seems to commit to some version of instrumentalist anti-realism. We could then in principle reply to the objection on this very general ground. It is worth noting that in this very case another reply can be advanced against the

objection presented. This reply has nothing to do with the general charge of instrumentalism. It is rather a very specific reply. Suppose we remove beamsplitter BS_2 and we position beamsplitter BS_4 back in its original place. Then the state at t_4, after the usual post-selection will end up being:

$$(29)\ \Psi_{4ps*} = \frac{1}{2\sqrt{2}}(|3_A\rangle|1_B\rangle + i|4_A\rangle|1_B\rangle - |2_A\rangle|4_B\rangle - i|2_A\rangle|3_B\rangle)$$

In this case we will be able to *predict* which photon will be detected in D_3-D_4 at t_4 after D_1 or D_2 has clicked at t_3, that is we will be able to reconstruct the path of the photons using predictions rather than retrodictions, thus facing the objection.

So, we seem to have two broadly realistic arguments. Do they favor the same variants of realism? Do they rule out the same variants of realism and anti-realism? If not, what then is the scope of each argument? It is to these questions that we now turn.

4 A Tree Model for Realisms

Realist claims about a specific target domain are usually intended as claims about the (i) existence of the objects of such a domain and (ii) its mind independence[17]. Nonetheless target domains for realist and anti-realist positions can be the most varied. There are realist or anti-realist positions about composite objects, unobservable entities, possible worlds, properties, numbers, sets, events, temporal parts, boundaries, holes, particles, fields, waves, space, time, spacetime, shadows and the list could go on almost forever. We are naturally interested about realistic and non realistic interpretations of a very specific target domain, i.e. wavefunctions and quantum states Ψs, which are a typical example of a theoretical entity of a scientific theory. Thus the realism we are interested in here is an example of so called "scientific realism". Taken at face value the realist claims (i) and (ii) about the target domains we have listed are ontological claims.

So it seems that the very first, general distinction is the usual one between scientific realists and anti-realists. In loose terms we can label the following thesis as Quantum Realism (*QR*):

> (30) (*Quantum Realism QR*) The entity to which Ψ refers, whatever that entity is, exists (in some sense)[18].

Van Frassen (1980) famously argues that we will never have reasons enough to warrant and support our beliefs in unobservable entities of scientific theories. Van Frassen (1991) puts forward the same point in the particular case of quantum mechanics. His constructive empiricism would then count as anti-realist in this sense.

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[17] We are deliberately vague at this stage of the argument.

[18] It is not our purpose here to enter into the subtle distinctions and complications of the realism-anti-realism debate, but rather to put forward a simple, yet not perfect, classification of different varieties of realisms in the foundations of quantum mechanics. Also note that this formulation seems to be a variant of what has been called "entity realism". It should be noted that it is not possible to maintain entity realism without endorsing an at least partial "theory realism", since theoretical terms are backed in a given theoretical language.

Claim (30) is indeed general. For example it does not specify whether the entity to which Ψ possibly refers is an individual or a property, and if it does refer to a property it does not specify which property of which individual. It is to these distinctions that we now turn. There are at least two candidates on the market for being the reference of Ψ, i.e. an individual and a property of some quantum system respectively. We can give a general formulation of *Individual Quantum Realism* as follows:

(31) (*Individual Quantum Realism IQR*) Ψ refers to a physical individual

Different versions of *IQR* are indeed possible depending on what kind of individual Ψ is taken to refer to. Schrödinger originally thought of the wavefunction as representing a tangible, physical almost classical wave. De Broglie (1958), Selleri (1969 and 1982) envisage the possibility of it referring to a particular kind of non classical wave, called empty or quantum wave. A different and radical contemporary version of *IQR* is known in the debate as *Wavefunction Realism*. The clearest and most compelling defense can probably be found in Albert (1996) and Lewis (2004)[19]. We quote from the latter: "the quantum mechanical wavefunction is not just a convenient predictive tool, but is a real entity figuring in physical explanations of our measurement results […] that exists in a many-dimensional configuration space" (Lewis, 2004: 713). It is clear from the last part that Lewis is suggesting that the wavefunction represents an individual rather than a property. Moreover there are several passages in the article in which he talks of the distribution of the wavefunction stuff. Everett (1957) can probably be considered yet another variant of *Wavefunction Realism*. These three proposals, despite their being variants of *IQR*, are profoundly different. This difference is particularly striking in the case of *Wavefunction Realism*. This is because this last variant is committed to *Configuration Space Realism*, i.e. to the claim that though the world appears three (or four) dimensional to us, it is really in the n-dimensional configuration space that we live in. A standard argument from *Wavefunction Realism* to *Configuration Space Realism* is a separability argument (Lewis, 2004: 715).

Consider two indistinguishable particles 1 and 2 constrained to move along one dimension. The wavefunction determines, via the Born rule, the chance to find the particles in regions A, B. Consider now the configuration space of the composite system, where the *y* axis represent the positions of particle 1, whereas the *x* axis that of particle 2. The following two cases are possible:

  (i)   The wavefunction intensity is large at regions (A, A); (B,B).
  (ii)   The wavefunction intensity is large at regions (A, B); (B, A).

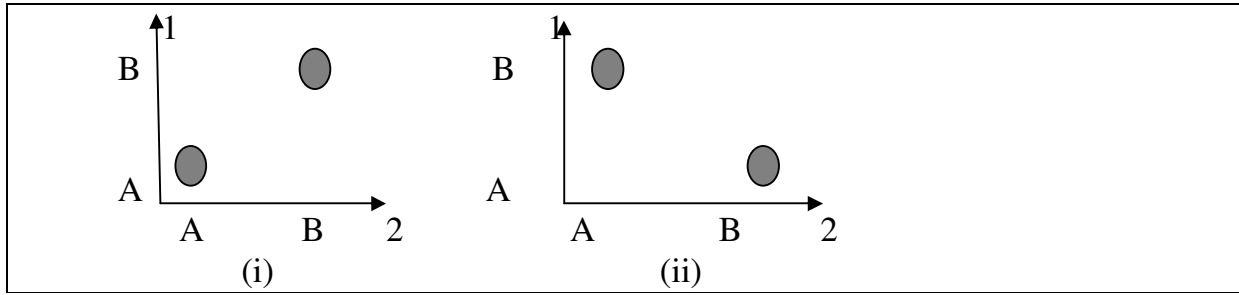[19] These last two works are discussed and criticized at length in Monton (2006).

Fig. 3: the Separability Argument

The corresponding wavefunctions to states (i) and (ii) are:

(i) $\frac{1}{\sqrt{2}} (|A\rangle_1|A\rangle_2 + |B\rangle_1|B\rangle_2)$

(ii) $\frac{1}{\sqrt{2}} (|A\rangle_1|B\rangle_2 + |B\rangle_1|A\rangle_2)$

According to *Wavefunction Realism w*avefunction (i) is a different individual with respect to wavefunction (ii). But when projected into the coordinates of individual particles (i) and (ii) generate the very same individual wavefunctions. Yet states (i) and (ii) represent for the wavefunction realists different distributions of the "wavefunction stuff" that actually explains why the particles positions are (i) perfectly correlated and (ii) perfectly anti-correlated. Hence configuration space cannot be simply a useful mathematical tool to represent physical situations, for the differences between configuration space representation (i) and (ii) do not represent differences in our knowledge of the particles' positions, but rather different physical situations. As Lewis (2004: 716) puts it: "Wavefunction realism commits us to the existence of a configurations space entity as a basic physical ingredient of the world".

On the other hand Schrödinger's, De Broglie's and Selleri's *Wave Realism* does not commit to the reality of the configuration space[20]. So, we have argued that different versions of *IQR* can have different ontological commitments[21].

Note that it seems that also the AT argument of section 3, insofar as it compels a realist interpretation, can be read as an argument in favor of *IQR*[22]. This is perhaps what the authors have in mind when they write that there is no reason not to attribute reality to the wave (Auletta and Tarozzi, 2004: 93). However it seems to us that AT does not favor the last variant of *IQR*, *Wavefunction Realism*, but rather can be seen as a contemporary heir to De Broglie's and Selleri's quantum waves.

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[20] Even though Schrödinger was never able to provide a purely wave interpretation for many bodies, that is when physical space does not coincide with configuration space. Note moreover that in Schrödinger's ontology there are only waves, whereas for De Broglie and Selleri waves are supported by particles.

[21] There is also an *IQR* concerning individuals as particles.

[22] AT could also support *InPSQR*, of which we are going to speak.

On the other hand Ψ can refer to a property or a set of properties, rather than an individual. We can label this *State Quantum Realism* (*SQR*):

(32) (*SQR*) Ψ refers to, or describes, a state of a given individual or system.

It is worth noting that this distinction does indeed make sense. If wavefunctions are individuals it follows that two different individuals cannot be, strictly speaking, represented by the same wavefunction, whereas it is possible that if wavefunctions represent states, i.e. properties of given systems, the same wavefunction can be attributed to numerically distinct ones. This is actually crucial in the PBR argument, as we have seen in section 2, for the argument depends on the possibility of duplicating the quantum system at hand via the same procedure, and hence in the same pure quantum state. This highlights an important trait in the ontological commitments of the PBR argument. Let us now move on to some further distinctions.

If the wavefunction gives a complete description of the system in question then we talk about *Complete State Quantum Realism* (*CSQR*). We probably need a more rigorous characterization of this completeness requirement. Here we draw again on Harrigan and Spekkens (2007). As in section 2 let a quantum system *QS* prepared via procedure *P* be in the pure state |φ⟩. Then its associated ontological state is given by a point λ in the ontological state space Λ. We say that |φ⟩ is a complete description of *QS* if the projective Hilbert space P$\mathcal{H}$ of *QS* and the ontological state space of *QS* are isomorphic, i.e.:

(33) (*Complete Quantum State*) The state |φ⟩ of a quantum system *QS* is complete if there exists an isomorphism f: P$\mathcal{H}$ ↔Λ.

Naturally enough |φ⟩ does not give a complete description of the system if it is not complete. Thus we can distinguish between *Complete State Quantum Realism* (*CSQR*) and *Incomplete State Quantum Realism* (*InSQR*):

(34) (*CSQR*) Ψ refers to a complete state.

(35) (*InSQR*) Ψ does not exhaust the ontological state.

Despite the fact that definition (33) is cast in terms of states, i.e. properties of a system, it could easily be amended to refer to individuals as well. This would help to classify wavefunction realism and wave realism even better, since the first would count as a variant of *Complete Individual Quantum Realism* (*CIQR*), whereas the second as a variant of *Incomplete Individual Quantum Realism* (*InIQR*).

Now, let us go back to section 2 for the distinction between physical quantum state and statistical quantum states. It follows from (33) and definition (1.1) of physical state that all complete states are physical, whereas it follows from (33) and definition

(2.1) of a statistical state that all statistical states are incomplete, i.e. the two following conditional hold[23]:

(36) Complete Ψ → Physical Ψ

(37) Statistical Ψ → Incomplete Ψ

Thus, if we define the following thesis *Physical State Quantum Realism* (*PSQR*) and *Statistical State Quantum Realism* (*StSQR*) respectively:

(39) (*PSQR*) Ψ refers to a physical state

(40) (*StSQR*) Ψ refers to a statistical state,

it follows that *Complete State Quantum Realism* is committed to *Physical State Quantum Realism* and that *Statistical State Quantum Realism* is committed to *Incomplete State Quantum Realism*. This naturally suggests the questions of whether the converses hold as well. It is evident that the answer is in both cases "no". For, if the state is physical it could be incomplete, as in the case of hidden variables deterministic theories, and if the state is incomplete it could be non statistical, again as in the case of hidden variable deterministic theories.

All these considerations suggest the straightforward definitions of *Complete Physical State Quantum Realism* and *Incomplete Physical State Quantum Realism*:

(41) (*CPSQR*) Ψ refers to a complete physical state.

(42) (*InPSQR*) Ψ, though it does not refer to a statistical state, does not exhaust the ontological state.

On the contrary, if the state is statistical it must be incomplete. So we have the following obvious definition:

(43) (*InStSQR*) Ψ refers to an incomplete and statistical state.

Harrigans and Spekkens (2007) mentions Beltrametti's and Bugajski's (1996) model as a prominent example of *CPSQR*. Here we can safely add Pusey, Barret and Rudolph (2011), which claim to have shown that *InStSQR* is incompatible with the predictions of quantum mechanics. Most hidden variables proposals, such as Bell (1966) and Mermin (1993) fall under *InPSQR*. Bohm (1957) also falls under *InPSQR*. He is actually particularly explicit in denying *Wavefunction Realism*. He writes: "While our theory can be extended formally in a logical consistent way by introducing the concept of a wave in a 3N-dimensional space, it is evident that this procedure is not really acceptable in a physical theory" (Bohm, 1957: 117). Harrigans and Spekkens (2007) lean towards *InStSQR,* but it is unclear whether they are fully committed to it. They mention however as significant examples a two-dimensional

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[23] See Harrigans and Spekkens (2007: 5).

model proposed by Kocken and Specker (1967) and also Albert Einstein attitude toward quantum mechanics: "I incline to the opinion that the wave function does not (completely) describe what is real, but only a (to us) empirically accessible maximal knowledge regarding to which [sic!] really exists" (*Einstein Archive*, 10-583; quoted in Howard, 1990: 103). However Einstein's position was probably more complex than these words actually depict.

There is moreover, as far as we can see, a further distinction, that is probably a very general methodological distinction that cuts across the board in the realistic field. It is the distinction between what can be labeled *Conservative* and *Progressive Realism*. Though precise definitions of such attitudes may be difficult to pin down we can try to provide some general characterization. These are our proposed formulations:

> (44) (*Conservative Realism*) A quantum realistic perspective is conservative if it maintains the completeness of the quantum wavefunction, that is, it maintains that for each quantum system there is an isomorphism between the projective Hilbert space of the system and the ontological space.

On the other hand we have:

> (45) (*Progressive Realism*) A quantum realistic perspective is progressive if it is not conservative, i.e. if it maintains that there are quantum systems such that their ontological space is either different or richer than projective Hilbert space. Both the exceeding part of the ontological space and its completely new structure must be described in a rigorous metaphysical language.

To have an historically infamous example of what we label *Progressive Realism* think of the *Reality Principle* in the original EPR paper (Einstein, Podolski, Rosen, 1935: 777). This principle, roughly states, that if the value of a particular observable can be predicted with probability =1, then there is an element of reality corresponding to it. This has been labeled (mistakenly) Einstein's realism. We actually know it can instead be attributed to Podolsky (Fine, 1986, p. 35). So we can affirm that *Podolsky Realism*[24] is a prominent example of *Progressive Realism*. The Reality Principle is in fact a rigorous metaphysical hypothesis formulated outside the framework of quantum theory that enriches the ontological space of quantum theory itself.

Even with these loose characterizations we can appreciate some important consequences. The first is that in general *Complete* forms of *Quantum Realism* are conservative, whereas *Incomplete* are progressive. The second is, we contend, that a progressive attitude is, methodologically, preferable overall. This is because it leaves open a great deal of options for future scientific investigations to explore. This openness is of paramount importance, since we cannot consider quantum mechanics a completely satisfying physical theory.

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[24] According to Fine, "Einstein's realism" is Podolsky's formulation of an idea that Einstein's endorsed during the discussion of the paper, but was not his definitive opinion.

Going back to our proposed classification of different quantum realisms it is now meaningful to ask whether they are an example of *Conservative* or *Progressive Realism*. There may be room for disagreement here. Some proposals however seem less contentious than others. It seems for example that *Wavefunction Realism* is conservative. On the other hand De Broglie's and Selleri's suggestion to introduce a new kind of individual, a quantum wave, to account for some quantum behaviors seems progressive[25]. All hidden variables interpretations count as progressive for the very same reason. On the other hand what we label *Complete Physical State Quantum Realism* can probably be counted as conservative. The results of this section can be represented by a very simple tree model (Fig. 4).
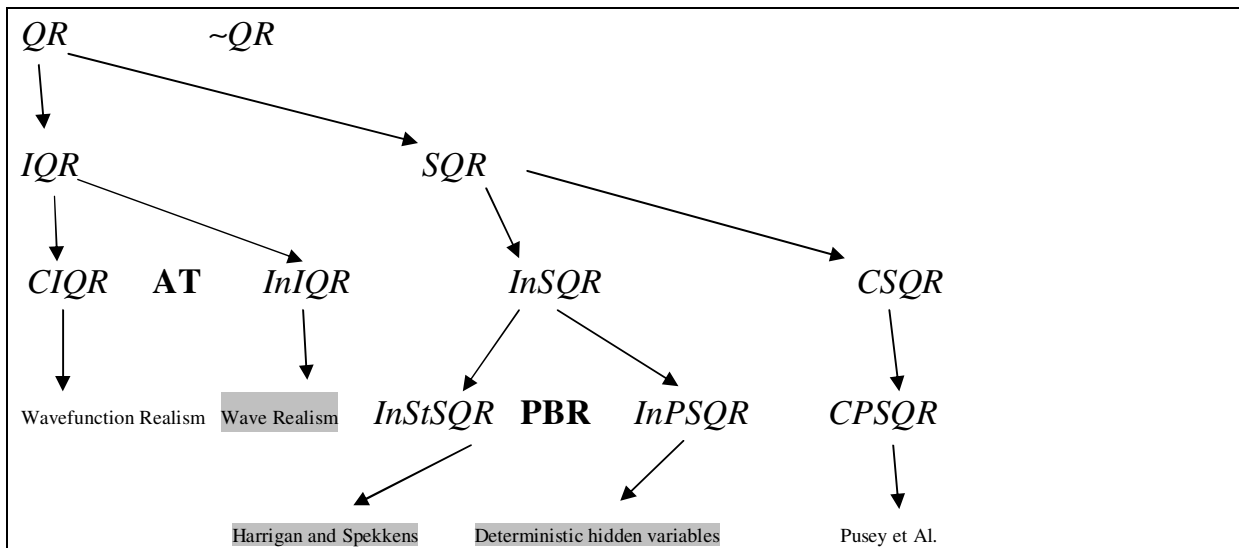

Fig. 4 Tree Model for Realism(s)

Shaded areas indicate that this kind of realism is progressive, otherwise it is conservative. Moreover note that the AT argument makes possible to decide between contemporary wavefunction realism (Everett, Lewis etc.) and classic wave realism (Schrödinger, De Broglie and Selleri), whereas the PBR argument acts a level lower in the tree model, since it allows us to decide between statistical and physical quantum realism.

As is usually the case with simple models such as this, it should not be expected that every possible position is represented and accommodated with perfect adequacy within the model. It has however the virtue of giving us a fairly simple model that (i) seems to capture most of the influential views held by the fathers of quantum theory and their modern heirs and (ii) enables us to assess in a fairly simple, yet naturally not decisive, way the scope of a realist or anti-realist argument in the foundations of quantum mechanics. The scope of an argument can in fact be taken as a function of

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[25] Since we are inclined to read the AT argument in the same spirit, they count as progressive too.

the logical place it occupies within the simple tree model. Let us clarify what we mean by "the logical place of an argument within the tree model". The model has a root and different branches. It has also knots that are where different branches do or do not depart. The logical place for an argument is the furthest knot from the root from where there are no two different departing branches. This also shows which branches are "cut off", so to speak, by the argument in question. In other words it shows which options the argument rules out as non viable.

It immediately follows that the closer to the root the logical place of an argument is the wider its scope. And, conversely, the more options it is able to rule out. "Stay closer to the root and you will cut off more branches" is the moral. And from this analysis it follows that the PBR and AT arguments have different scopes. The first might be stronger but the second is wider.

5 Conclusion

Let us sum up what we have done in this paper. We have reviewed and extensively discussed two recent arguments that could be read as realistic arguments within the foundations of quantum mechanics. We have then presented a possible classification of different realist positions and suggested that the arguments favor two different variants of realism. If so, we have contended, the argument for the particular variant of realism which we labeled "wave realism", is wider in scope. Also, the arguments we have used throughout the paper make it clear that both of the arguments can be resisted by appealing to general anti-realistic strategies such as endorsing either semantic or epistemic antirealism. There are several things that we have not discussed. We have not discussed some major philosophical implications of the arguments. The PBR argument seems to imply that different quantum pure states represent different states of reality. Now, superposition states can be pure states. It follows that we should develop a theory of property instantiation that is adequate to provide a positive account of such a situation. In other words we are now driven with more force to say something positive about what it is to be in a superposition state, rather than confining ourselves to negative statements such as "if the quantum system is in a superposition of spin up and spin down it is not definitely spin up, is not definitely spin down, and it is neither definitely spin up *and* spin down nor spin up *or* spin down". On the other hand if the AT argument is sound and quantum waves have some sort of ontological reality we are left wondering whether they depend ontologically on the existence of particles, or whether they do not. Or more generally we are left wondering about the relation between a particle-like ontology and a wave-like ontology. Not to mention other well known difficulties concerning *Wavefunction Realism*[26]. So, there is a lot more to talk about. But another time.

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[26] See again Monton (2006).

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