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The Recently Claimed Observation of Atomic Orbitals and Some Related Philosophical Issues

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The main thrust of the paper involves a theoretical and philosophical analysis of the claim made in September 1999 that atomic orbitals have been directly imaged for the first time. After a brief account of the recent claims the paper reviews the development of the orbit and later orbital concepts and analyzes the theoretical status of atomic orbitals. The conclusion is that contrary to these claims, atomic orbitals have not in fact been observed. The non-referring nature of modern atomic orbitals is discussed in the context of Laudan's writings on realism, the success of theories, and whether or not scientific terms refer. I conclude that the failure to observe orbitals is a good *prima facie* case for divorcing the success of theories from the question of whether their central terms refer. The added relevance of this case is that it concerns a current and highly successful theory. Finally, the relevance of this 'floating model' to contemporary discussions on scientific models is briefly considered.

1. Reports Claiming That Atomic Models Have Been Directly Observed.

The recent dramatic claims made in *Nature* magazine to the effect that atomic orbitals have been directly observed fly in the face of conventional wisdom regarding the nature of such theoretical entities. Of course this alone does not represent grounds for dismissing such claims. However, if these claims were to be sustained it would imply an outright refutation of quantum mechanics, which does not appear to be the intention of the authors concerned.

Unlike the infamous and recent case of cold fusion, the claims made for the observation of atomic orbitals were not presented at a press conference but, as mentioned above, were announced in the world's most

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prestigious scientific news journal. The front page of this issue of *Nature* featured the simple words “Orbitals observed” in large bold letters, alongside some images taken from the primary article, which states:

[T]he correspondence between our experimental map and the classical diagrams of d_z^2 orbitals sketched in textbooks is striking. All our difference maps show strong non-spherical charge distributions around the copper atoms, with the characteristic shape of d orbitals. (Zuo et al. 1999, 51)

An accompanying editorial article in the same issue of *Nature* shows less, if any, reservation concerning the identification of the images obtained with textbook orbitals. The headline caption for the editorial begins,

The classic textbook shape of electron orbitals has now been directly observed. (Humphreys 1999)

This is followed by the statement that

[f]or the first time the striking shape of some of the electron orbitals is revealed experimentally. The paper by Zuo et al. is remarkable because the quality of their charge-density maps allows, for the first time, a direct experimental ‘picture’ to be taken of the complex shape of the d_z^2 orbital. (Humphreys 1999, 21)

Other quality science magazines as well as trade journals have shown even less caution in reporting the orbital claims emanating from Arizona State University. A web page produced by a respected popular science magazine states boldly:

The idea of orbitals has long proved useful for describing atoms and their interactions mathematically, but not physically. Now all that’s changed. Researchers at Arizona State University recently published in *Nature* the first true images of atomic orbitals in Cu_2O , a crystal called cuprite. (<http://www.sciam.com>, 1999)

An article appearing in *Chemical and Engineering News* begins with:

Remember the really neat-looking d-orbital from freshman chemistry? The one that looks like a three dimensional figure 8 with a doughnut around its midsection? Well, it’s just been experimentally observed by Scientists at Arizona State University at Tempe. (Jacoby 1999, 8)

In addition, the primary researchers have insisted, in various quoted remarks, that they are indeed directly imaging “textbook orbitals” rather than mere electron density or computer generated images of orbitals.¹

1. The lead author from the primary article in *Nature*, J. M. Zuo, is quoted as saying,

Whatever the motivations for such claims might be is not a matter to be entered into in this article. We merely wish to suggest that, as currently understood, in the standard interpretation of quantum mechanics, orbitals cannot possibly be observed.²

2. A Brief History of Atomic Orbits and Orbitals. Once upon a time, at the beginning of the twentieth century, several scientists happened on the idea that the structure of the atom might be analogous to that of the solar system, with electrons acting as planets orbiting around the nuclear sun. This idea was first discussed by Jean Perrin in France, while Hantaro Nagaoka in Japan suggested a Saturnian atom with rings of electrons. The now famous experiment performed by Rutherford, on the scattering of alpha rays by a piece of gold foil, provided support for the model of orbiting electrons. Thus the atomic orbit, one of the most enduring metaphors of our age, was born.

Niels Bohr used the notion of atomic orbits in his theory of the hydrogen atom and even gave an approximate explanation for the form of the periodic table of the elements, by appealing to electron orbits in many-electron atoms (Scerri 1997). However, he himself soon realized that such electron orbits in atoms larger than hydrogen would have to be regarded as only useful approximations.

The advent of quantum mechanics at the hands of Heisenberg, Schrödinger, Born, and others provided a more abstract picture of the atom. Now electrons were to be thought of as being in three-dimensional orbitals, in which the change in terminology would denote an important conceptual change. Unfortunately the change in terminology has not been radical enough, with the result that many scientists and educators, at many levels of enquiry, appear to retain a realistic notion for the new concept of an orbital in the sense of electrons undergoing a trajectory. Following Heisenberg the exact location of the electron could no longer be specified. This finding, together with the probabilistic interpretation of quantum mechanics, led to the introduction of probability clouds to represent orbitals. The brief sketch of the historical development of atomic physics is

“It’s direct experimental proof of the quantum model.” This is in an article entitled “Observing Orbitals”, with the subtitle, “The first pictures of atomic orbitals are confirming theories and resolving controversies”. In fact it has been articles such as this one that have fueled a new controversy regarding whether orbitals exist physically or not.

2. There has been almost unanimous agreement among participants of several Internet discussion lists that orbitals cannot possibly be observed. These lists include hopos, philchem, chemed, and the history of chemistry server. Professional theoretical chemists do not even see much need for discussion since in their view the issue is quite clear-cut in that orbitals are simply unobservable. Several individual theoreticians whom I have contacted directly agree on this point.

all too familiar. But what is not often appreciated is that Heisenberg's discovery sets limits on the accuracy with which the position and momentum of an electron can be specified but does not rule out an electron trajectory in principle. The result of this confusion is that some people seem to believe that the electron still maintains a definite trajectory but that we merely cannot specify this trajectory precisely. In fact, there are strong reasons for ruling out electron trajectories which do not depend on Heisenberg's principle.

2.1. The Orbital Model As an Approximation. The quantum mechanical revolution also implies a more technical modification to our view of microscopic phenomena. Whereas the old quantum theory, as perfected by Pauli, required the assignment of as many as four quantum numbers to each electron in a many-electron atom, the arrival of quantum mechanics showed that even this more abstract notion is strictly inconsistent in any atom other than hydrogen. This result can be expressed by saying that individual electrons in a many-electron atom are not of themselves in stationary states whereas the atom as a whole does possess stationary states. This change in perspective is far from trivial and shows definitively that the orbital model is an approximation in many-electron systems. It also requires that the scientific term 'orbital' is strictly non-referring with the exception of when it applies to the hydrogen atom or other one-electron systems.³

Unfortunately this part of the message from quantum mechanics has not been readily assimilated and many professional chemists and even physicists are still not clear about the issue.

3. The Modern View of Orbitals Among Experts. Even so, the fact that orbitals in the modern sense of the term represent an approximation in many-electron systems does not provide sufficient grounds for my earlier categorical claim that orbitals cannot be observed under any circumstances. I will return to this point in due course. The continuing value of orbitals lies in their serving as basis sets, or a form of coordinate system, with which the wavefunction of an atom, ion, or molecule can be expanded mathematically to any degree of accuracy dictated by the available computational power. Orbitals have not only lost their former pictorial aspect which they possessed at the beginning of the century when they were still called orbits, but now even the mere assignment of electrons to specific orbitals, or electronic configurations, as regularly carried out in chemistry and physics has lost its physical significance. Of course, the orbital model remains enormously useful as an approximation and lies at the heart of

3. For example the ions He^+ , Li^{+2} , or Be^{+3} .

much of quantum chemistry but it is just that—a model, without physical significance, as all computational chemists and physicists are well aware (Scerri 1991, 2000). Atomic orbitals also serve as a means of classifying spectroscopic transitions in the study of atomic spectra (Condon and Shortley 1935).

In fact, only the atom as a whole possesses well defined stationary states and these states are characterized by the vectorial coupling of individual electronic momenta, with different coupling schemes operating depending on the kind of atom in question.⁴ In addition, the usual textbook statements which refer to particular numbers of electrons in particular orbitals, such as 1s, 2p, or 3d orbitals, are in strict violation of the Pauli principle, which maintains that all electrons in the system are indistinguishable. These shortcomings of the orbital concept are counteracted, to some extent, by means of the permutation of all the electrons in the course of Hartree-Fock calculations. If one insists on retaining a physical picture this would correspond to the view that each electron is in every single orbital simultaneously. But even this procedure does not succeed in including the residual and significant effect known as dynamic correlation between electrons. To do so requires the use of more sophisticated mathematical techniques, some of which go beyond the orbital approximation.⁵

In modern theory, atomic orbitals serve merely as basis sets, that is, as forms of coordinate systems which can be used to expand mathematically the wavefunction of any particular physical system. Just as the coordinate system of x, y, and z used to describe any particular experiment in classical physics is unobservable, so too atomic orbitals are completely unobservable even in principle. What can be observed, and indeed is frequently observed in experiments, is electron density.

3.1. Back To the Recent Claims. In the recently announced experiments the authors have fit experimental X-ray and electron diffraction data to a

4. The strictly non-referring nature of atomic orbitals can be expressed through the following mathematical equation:

$$[H, l_x] \neq 0.$$

This states that the operator corresponding to the angular momentum of any particular electron does not commute with the Hamiltonian of the system. As a result, individual electrons are not in genuine stationary states, although the ensemble of all the electrons possess genuine stationary states.

5. The failure to include correlation energy in a typical atomic calculation results in an error of approximately one percent in the total energy of an atom. This may seem insignificant but it is not, especially as typical bonding energies amount to about one percent of total atomic energies. A calculation which fails to include correlation energy can thus fail to predict whether bonding occurs or not between the atoms of any two particular elements.

model called multipole refinement. This method does not assume an actual sum of atomic contributions but fits the data by an expansion in terms of radial functions multiplied by spherical harmonics on various centers. The result is a charge density which is then compared to that obtained as a superposition of spherical atomic contributions, assuming that the compound is perfectly ionic. The density difference map is thus obtained as the difference between the experimental fit and the spherical or purely ionic fit (Coppens 1997; Tsirelson and Ozerov 1996).

My aim is not to deny that the techniques reported may have thus provided an image of overall electron density in the copper compounds in question but only to question whether

[t]he classic textbook shape of electron orbitals has now been directly observed (Humphreys 1999, 21),

to cite again the editorial in *Nature*, and the suggested linking of the images obtained with 3d orbitals in the primary paper.

Although the primary authors may not have made the explicit claim of having observed atomic orbitals, it seems a little odd that they should have expressed their findings in such a suggestive and, as it has turned out, rather misleading manner. It is also rather odd that in all their quoted remarks which have appeared in other magazines, and even newspapers, the authors have done nothing to deny, or at least diminish, the reports that they have in fact directly observed some orbitals.

I suggest that any similarities between the reported images and textbook orbitals may be completely coincidental.⁶ As philosophers are well aware, scientists are often quick to draw realistic conclusions from their experimental findings. However, it is essential for scientists to be more discerning in attributing physical reality to entities which are defined theoretically and which the theory itself informs us do not exist physically. It is also rather unfortunate that popular science journals from which many philosophers and science educators rightly draw scientific information should have misrepresented the recent findings. But as I suggested earlier this is not entirely surprising in view of the way that the results were first communicated.

6. Interestingly, John Spence, the leader of the Arizona State team responsible for the alleged observation of orbitals, has conceded as much in a recent personal correspondence (16 September, 1999) when he writes,

[M]y own feeling is that there is little chance of educating non-specialists on these issues. The one-electron picture is too ingrained in most scientists' thinking (and too useful in many cases!) to be eradicated. And the fact is that the measured valence charge density (difference) in cuprite does actually resemble a d_x^2 "orbital" hole, however fortuitous that may be.

4. More About the Nature of Atomic Orbitals. First of all the term ‘orbital’ is a highly generic one. It is used to describe hydrogenic orbitals, Gaussian orbitals, natural orbitals, spin orbitals, Hylleraas orbitals, Kohn-Sham orbitals, and so on. All incidentally are unobservable *in principle*.

The hydrogenic variety of orbitals comes from the exact solution of the non-relativistic Schrödinger equation for the hydrogen atom. I propose to focus on these orbitals since the claim by the Arizona State scientists concerns the observation of 3d orbitals, which represent one kind of hydrogenic orbital. The nature of quantum mechanics is such that it features operators, eigenfunctions, and eigenvalues, and only the last of these are observable. Orbitals are eigenvectors, or more specifically, the components out of which eigenvectors are constructed. In the case in point it is only the values of quantum numbers which can be observed. For example, the specification of a 3d orbital requires the assignment of three distinct quantum numbers, as is well known. These are $n = 3$, $\ell = 2$, and m_ℓ , which can take any of 5 values ($-2, -1, 0, 1, 2$) depending on which d orbital is identified. In a many-electron atom this type of 3 quantum number (4 if spin is included) description breaks down. For example, in a system where there is no spin-orbit coupling but only Coulombic interactions, that is to say, only electron-electron interactions, it is necessary to consider the vectorial sum of the separate ℓ , m_ℓ , and m_s quantum numbers. The observable corresponding to angular momentum, denoted by capital L, is obtained as a vector sum of the individual ℓ 's. But this ‘observable’ will not correspond to, that is, will not be characteristic of, the shape of a d orbital or even s or p. If anything it will correspond to a composite shape due to contributions from the shapes of all the orbitals. Contrary to the frequently seen textbook representations, the atom does not retain the appearance of a set of concentric orbital shapes consisting of the 1s, 2s, 2p orbitals, etc. In fact they all combine together and there is therefore no reason to expect that the eigenvalues obtained will correspond to an outer envelope with the shape of a d orbital, let alone the supposedly observed $3d_z^2$.

The term ‘orbital’ thus has a specific theoretical meaning and just because the images obtained, following much data processing, roughly correspond to what might loosely be termed ‘orbitals’ is no reason for making such an identification. Identity does not come in degrees but is an all-or-nothing affair. Those who are suggesting that we should make this kind of identification are guilty of making a category mistake.

5. Orbitals and the Question of whether Successful Theories Imply Referring Theoretical Terms. In this final section I turn to the question of realism and specifically the discussion regarding whether the theoretical terms which appear in scientific theories genuinely refer or not. In fact my aim is more specific since I will be concentrating on whether it is the case that

successful scientific theories imply that the terms employed refer. Here I will be considering atomic orbitals as my main example of theoretical terms.

In order to pursue this question I focus on a much cited article in the literature, namely, Larry Laudan's "A Confutation of Convergent Realism" (Laudan 1981). I will take up some of his points in order to see whether the case of atomic orbitals casts any new light on the issue or whether it might even serve as a different kind of example. I do this because I believe that a stronger case can be made for divorcing the question of whether theoretical terms refer from the question of the success or otherwise of the theories in which such terms are featured.

Laudan asks whether, as a matter of historical fact, successful past theories always possess referring terms in the sense generally taken by realists. He provides numerous examples to show that this has generally not been the case. For example, Laudan cites several ether theories and other influential theories from the eighteenth and nineteenth century, like phlogiston and caloric, which were successful but possessed non-referring central terms from a modern perspective. Laudan does not however venture to make such an argument for any twentieth century theories or even less for any currently accepted theories in science.

Of course in the historical cases cited by Laudan, the realist can claim that the terms may not have referred but that something which survives in the currently accepted theory did refer and that this explains why the older theory enjoyed some previous success. I will return to this 'retention' issue below.

But first I will pursue my main goal. I want to argue that Laudan's case is even stronger than he seems to believe, and even applies to the most successful and far reaching scientific theory which has ever been devised, namely, quantum mechanics. Of course the critic can respond by pointing out that the term 'orbital' is only one of many used in modern quantum chemistry and physics. But Laudan himself has provided a response to those who might doubt whether an argument based on just one theoretical term belonging to any theory should carry any persuasive power in writing:

After all, part of what separates the realist from the positivist is the former's belief that the evidence for a theory is evidence for *everything* the theory asserts. . . . For realists like Boyd, either all parts of the theory (both observational and non observational) are confirmed by successful tests or none are. In general, realists have been able to utilize various holistic arguments to insist that it is not merely the low-level claims of a well-tested theory that are confirmed but its deep-structural assumptions as well. (Laudan 1981, 226-227)

Put in other words, this implies that if one term fails to refer, this feature has a bearing on the whole theory and cannot be conveniently put to one side.

In any case there is no denying the ubiquity of the theoretical term 'orbital' in modern quantum chemistry. As I mentioned briefly earlier in the article there are many kinds of orbitals such as hydrogenic, Hylleraas-type, natural orbitals, spin orbitals, and so on. Indeed there is hardly any computational work carried out in quantum chemistry which can genuinely be said not to use some kind of orbital method.

It should by now be clear from the preceding sections that the generally accepted view of atomic orbitals is that they are strictly non-referring in that they do not pick out any entity which may be said to physically exist in the same sense that a planetary orbit exists. This does not, however, diminish their usefulness in a multitude of computational schemes employed in quantum chemistry or their applicability to the classification of spectroscopic transitions and to a discussion of a plethora of chemical and physical phenomena. In addition, much of the success of modern quantum chemistry, including the award of the 1998 Nobel Prize for chemistry, is directly attributable to the use of calculations based on atomic and molecular orbitals.

By restricting himself to defunct theories Laudan cannot carry his argument through as successfully as he might. This is because he leaves open the possibility for the realist to claim that successful past theories are always replaced by theories that preserve reference even if the precise nature of the referent changes with the change of theories. This is the argument which sometimes appeals to the example of theories of the electron. It is of no importance, the realist claims, if the electron theory is Thomson's, Rutherford's, or Bohr's since although the precise description of the particle may change the actual referent has remained constant.

I claim that atomic orbitals provide an interesting *prima facie* case against this view since they began life as well defined referential terms in Bohr's, and even older theories of atomic structure, only to lose their ability to refer with the advent of quantum mechanics. It does not matter whose orbitals are selected from the modern palette of choices since *none* of them refer. The realist cannot therefore claim that reference has been preserved in the same way that she might in the case of electron theories.

It should be noted that at least some philosophers of science do contemplate the possibility of divorcing reference from the success of scientific theories. Such is the case with Hardin and Rosenberg in their critique of Laudan's article that I am considering here (Hardin and Rosenberg 1982). But as Laudan has properly responded, in my view, the price for such a divorce is that it leaves the realist in a position which is hardly distinguishable from instrumentalism and it undercuts any possibility of making in-

ferences to the best explanation, which is the fundamental move bolstering the realist's overall position.⁷

Of course Laudan himself does want to divorce the success of theories from the question of whether their terms are referential. In arguing from cases in defunct scientific theories he is suggesting that this will also turn out to be the case in our current theories. Here Laudan appeals to his "Pessimistic Meta-Induction" to say that all theories will eventually be refuted and their terms will become non-referring. But as many authors have pointed out, the idea of a pessimistic meta-induction itself is open to criticism. It would therefore be advantageous to have a more direct argument for saying that an important term in quantum mechanics is non-referring even before the theory has been refuted. What Laudan has not availed himself of, however, has been any example from present-day highly successful science where the theory itself stipulates that a central term is non-referential. This is what I believe I am providing in this article.

The bottom line would seem to be that if orbitals could be directly observed then the realist would have won the elusive victory, since the term 'orbital' would be shown to be referential. Given the undeniable success of quantum chemistry, the realist would be able to claim that in one very important case, at least, success and genuine reference go hand-in-hand. Unfortunately for the realist camp the claimed observation has turned out to be a chimera. Whereas this fact this does not seem to be of great importance to the primary researchers, I believe that it is rather important to philosophers of science.

Of course if by some miracle it emerges that orbitals have after all been observed in the recent experiments, or any future ones for that matter, then all the arguments I offer here to disconnect the success of quantum mechanics from whether its terms refer will have collapsed completely. It is for this reason that I think that the recent claim deserves far more critical scrutiny than it has received up to now.⁸

6. Conclusion and the Question of Models. Recent work by philosophers seems to place less emphasis on linguistic aspects of theories as well as on the questions of realism and anti-realism and whether or not scientific terms refer. The modern approach has been to attend to semantic aspects of scientific theories, and most importantly, to examine the role of models within scientific theories. In view of this tendency it becomes all the more relevant to obtain a clear understanding of the status of one of the central

7. The 'no divorce' view which Laudan attributes to most realists is to be found expressed in the writings of Putnam, Boyd, and Newton-Smith, among others.

8. Up to the time of writing, I am not aware of a single critical evaluation of this episode in the philosophical literature.

models used in chemistry and physics, namely, the atomic orbital model or the independent-electron approximation as it is also termed.

Moreover, philosophers who are interested in models might want to consider a rather curious feature of the orbital model. I am referring to the fact that the orbital model has been called a 'floating model'. This term, first coined by Heinz Post (1974), aptly describes the somewhat ambiguous nature of atomic orbitals. The model is said to float because it is neither securely anchored theoretically nor empirically. As was described earlier, orbitals are not strictly derived from quantum mechanics in the case of many-electron systems. The approximation involves assuming that each of the electrons in a many-electron system moves in a resultant field consisting of the nucleus and all the other electrons apart from the one being considered.⁹ In this approximation one can return, approximately, to considering a many-electron system as a pseudo one-electron system. Only then can one return to using the 1s, 2s, 2p and other familiar orbital labels for solutions to the hydrogen atom problem which *do* have a secure basis in theory.

From the experimental side the floating nature concerns the fact that only quantum states, or more correctly, only transitions between such quantum states, are truly observable. Electronic configurations that are specified in terms of the occupation of atomic orbitals do not correspond to quantum states *except* in the case of the hydrogen atom. The measurement of atomic orbital energies in the case of atoms and molecules is generally carried out via the Koopman theorem, which states that the orbital energy is equal to the negative value of the ionization energy of any particular electron.¹⁰ But this too is an approximation since it depends on the counterfactual assumption that, on the removal of any particular electron from an atom or molecule, the remaining electrons do not experience any relaxation resulting from the resultant dynamical situation.

The newly announced experiments, like several others reported in recent years, may indeed show images of electron density, or differences in electron density, but not atomic orbitals, regardless of the claimed sophistication of the experimental techniques employed. I suggest that any similarities between the reported images and textbook orbitals are coin-

9. This is called the central field approximation or the Hartree-Fock model.

10. Koopman's theorem states:

The energy, I_r , required to remove an electron from an orbital Ψ_r , on the assumption that the other electrons do not adjust their distribution, is the negative of the one electron orbital energy ϵ_r ,

$$I_r \sim -\epsilon_r.$$

This so-called theorem is only an approximation because electrons do in fact relax into a new distribution on the removal of an electron.

cidental or results of theory-laden analyses of the data obtained. Both the *Nature* editorial feature by Humphreys and the primary article itself are mistaken in claiming, or strongly implying, that d orbitals have been imaged for the first time.

6.1. The Real Crux of the Matter. I have kept till last the most categorical reason for wanting to deny the possibility of ever observing an orbital. After all, the fact that orbitals might only provide an approximation to the motion of many-electron systems is not a sufficient reason for the complete denial that they or something related to orbitals can possibly exist. My final argument, which I claim to be the most decisive one, is that orbitals depict a quantity called probability amplitude, which has been known to be unobservable in principle since the birth of quantum mechanics as distinct from the old quantum theory.

Whereas the amplitude associated with classical wave motion such as sound waves or water waves corresponds to the 'height' of the crest of the wave, this is not so in the case of matter waves of which electron waves are an example. Here the term 'amplitude' is only used by analogy. For example, the intensity of a matter wave, or even a light wave, is not proportional to the square of the amplitude of the wave. This much has been known since Einstein's elucidation of the photoelectric effect in 1905 when it emerged that the energy of the X-rays which produce the photoelectric effect is proportional to their frequency and not their amplitude. The terms 'amplitude' and 'orbital' as used in quantum mechanics, with reference to matter waves, are both somewhat misleading since they wrongly suggest analogies with classical amplitudes or classical trajectories. An electron has neither of these classical properties and, most crucially for the purposes of the present paper, has no classical trajectory. Moreover the mathematical expression for most atomic orbitals involves the number i , (the square root of minus one), thus rendering the number imaginary. This is why one can only observe the square of an atomic orbital rather than the atomic orbital itself. The square of the square root of minus one is, of course, minus one, which is physically meaningful unlike i , which is imaginary. Or to state a general result of quantum mechanics which goes beyond just talk of orbitals, the wavefunction for any system is unobservable whereas the square of the wavefunction can be observed, since the act of squaring turns an imaginary quantity into a real one.

And if this was not enough it emerges that atomic orbitals are described in a many-dimensional Hilbert space which defies visualization since we can only observe objects in three dimensional space. How then can anyone still claim that orbitals have been directly observed? And yet this is just what was claimed in *Nature* magazine and many other journals without

the subsequent appearance of a single letter to the editor to contest this claim.

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