Australian Physics

VOLUME 60, NUMBER 1, JAN-MAR 2023

A CHALLENGE IN NONLINEAR OPTICS

CORRELATED METAL – ORGANIC FRAMEWORKS

WALTER BOAS MEDAL – QUANTUM APPLICATIONS

Quantum applications and implications

Howard Wiseman
Director,
Centre for Quantum Dynamics, Griffith University, Yuggera and Yugambeh Countries, Queensland.
Prof.Howard.Wiseman@gmail.com

The Walter Boas medal is given annually by the AIP for the "research making the most important contribution to physics" done in Australia in the preceding four years. The citation for Howard Wiseman's award in 2021 is: "For elucidating fundamental limits arising from quantum theory, in particular in its applications to metrology and laser science, and via its implications for the foundations of reality." As this indicates, the work for which the medal was awarded was quite varied. In the article below, Professor Wiseman concentrates on two highlights: Heisenberg-limited lasers and a theorem stronger than Bell's.

Applications to metrology and lasers

Quantum theory implies fundamental limits to the performance of technologies, from measurement devices to computers. However, those limits are often far beyond what is achieved with 'standard' ways of building and operating such devices. When the fundamental limit (called the "Heisenberg limit" in some fields) scales better than the standard quantum limit (SQL), in terms of some basic resource – like time, size, or energy – we talk of a quantum advantage. This brings with it the potential for vastly better technology.

The best-known example of a Heisenberg limit is that offering a quantum advantage in the measurement of a static optical phase. Here, by using non-standard techniques such as entanglement or a variable number of beam passes, it is possible to estimate an initially unknown optical phase with mean-square error scaling as $1/N^2$. This is quadratically better than the SQL in terms of N, which represents the total number of photon-passes through the unknown phase shift.

I've worked in quantum phase metrology a lot over the years, in particular on the utility of adaptive measurements, and often in collaboration with experimentalists. This was reflected in some of my research in the Boas Medal period [1,2]. But, more excitingly (for me at least), in 2020, I and co-workers proved a Heisenberg limit of a completely new kind: for the coherence C of a laser beam in terms of μ, the mean number of excitations in the laser in steady-state [3]. Here C is also a dimensionless number: the number of photons emerging in the laser beam within one coherence time – in loose terms, the number of emitted photons with approximately the same phase.

The standard quantum limit to laser coherence is C scaling as μ^2, as proven by Schawlow and Townes in 1958 [4]. But, by reconceptualising the laser as any device that

a) Produces a beam close to that of a standard ideal laser beam,

b) Has no external sources of coherence,

we showed that a coherence scaling as μ^4, was possible [3]. For large μ, this implies a vastly greater coherence than a standard laser with the same μ. The key to achieving this is to make both the gain and output mechanism of the laser highly nonlinear processes, in a very specific way; see Fig. 1. Moreover, we proved a theorem that for any device satisfying (a) and (b), μ^4 is the best possible scaling [3]. That is, μ^4 is the Heisenberg limit to laser coherence.

In addition, we proposed a method by which this scaling could, in principle, be realised using superconducting quantum devices at microwave frequencies. That is, it would create a Heisenberg-limited *maser*, recapitulating the original technological development of lasers [4]. Subsequently, but independently, others had similar ideas [5]. Funded by a 2022 Discovery Project, with experimental partners in France, we are now working towards realising this type of device. As part of this DP, another PhD student with me at Griffith is currently working on a scheme to surpass the SQL scaling in an *optical* frequency laser.

Implications for the nature of reality

At the other end of the spectrum in quantum science are the field's implications for our understanding of nature. The most famous example of this is Bell's theorem from 1964 [6]. In this Bell showed that, if certain quantum experiments were to work as expected, then the conjunction of a certain set of metaphysical

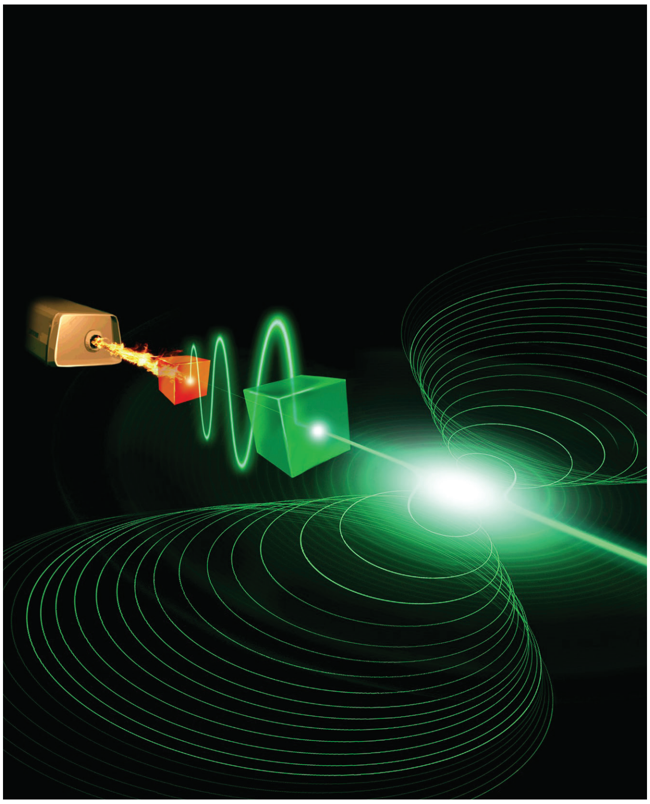

Figure 1: Artist's impression of a Heisenberg-limited laser, creating a highly coherent output from an incoherent input, by using non-standard gain and output processes. Credit: Ludmila Odintsova.

propositions – that is, basic statements about the nature of reality independent of any particular physical theory like quantum theory – must be false. Since 2015, when the first loophole-free Bell experiments were performed, we have been able to say that this set, in conjunction, *is* false. It was for one of these 2015 experiments, using entangled photon pairs, and its forerunners dating back to 1973, that the 2022 Nobel Prize in physics was awarded, to Clauser, Aspect, and Zeilinger.

There are many ways to choose the set of metaphysical assumptions that, in conjunction, Bell experiments rule out. Different authors go with different degrees of rigour and generality. For the purpose of this article, a convenient choice – quite general, and fairly rigorously stated – is the following:

(a) **Interventionist Causation.** If experimental interventions are made in a manner appropriate for randomized trials, then the only experimentally relevant variables that are correlated with the interventions are those of which the intervention is a cause.

(b) **Relativistic Causal Arrow.** Any cause of an event is in its past light-cone.

(c) **Absoluteness of Outcomes.** The outcome of a measurement is an *absolutely* real event, not relative to any-one/thing/world/branch.

d) **Causal Explanation.** If two variables are correlated then either one is a cause of the other or they have a common cause that *statistically explains* the correlation (in the sense that conditioning on the value of the common cause removes the correlation).

Note that the word 'cause' here does not have to be defined; its appearance in multiple propositions here is sufficient for the set, in conjunction, to imply the restrictions ("Bell inequalities") on correlations that have been violated experimentally. Note also that while (a) looks complicated, it is just a rigorous version of a sort of "free choice" proposition.

Now that loophole-free Bell experiments have been performed – proving that at least one of the four propositions, (a), (b), (c), or (d), must be false – what's next? As a warm-up answer, one future direction for Bell experiments is to replace proposition (c) by a *weaker* one, in which the property of absoluteness is required only for certain kinds of outcomes – the ones that we ultimately care most about [7]:

c') **Absoluteness of Observations.** An observation by a human being (or equally intelligent party) which can be communicated is an *absolutely* real event, not relative to any-one/thing/world/branch.

With this substitution, we can no longer say that the set (a,b,c',d) of propositions has been proven false experimentally, because intelligent parties are much slower at making observations than physical detectors are at producing outcomes. Thus (c') would require distributing entanglement to intelligent parties at much larger separations than has currently been achieved. However, such experiments, with one party on the moon for example, are certainly plausible in the medium-term [7].

Would such an experiment be worth doing? For most physicists, perhaps not. That is because, of either set (a,b,c,d) or set (a,b,c',d), most physicists already advocate giving up proposition (d). The reason is that standard quantum theory violates this proposition. In standard quantum theory, there are no common causes ("hidden variables" as they are often called) that statistically explain the correlations between space-like-separated measurements on entangled particles. And most physicists implicitly subscribe to a sort of scientific realism, in which the truth of a metaphysical proposition conforms to the truth of the corresponding

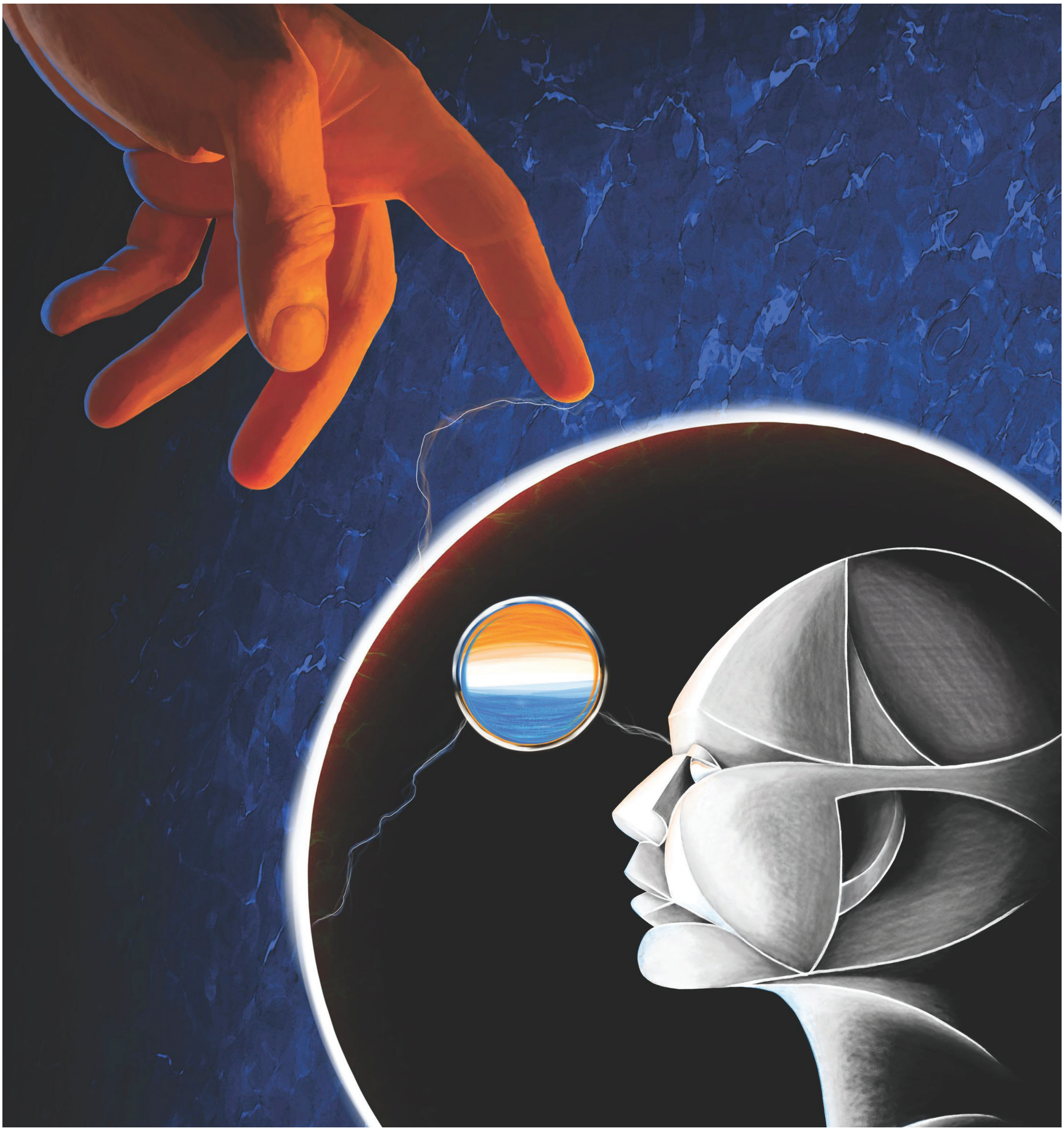

Figure 2: Artist's impression of a quantum computer instantiating an intelligent party who has observed a quantum system, perhaps about to be reversed at the whim of a human party. Credit: Tony Dunnigan.

proposition applied to our standard empirical description of physics (or other sciences).

Thus, I and my theory co-workers were shocked when, inspired by [8], we found a way to prove a theorem like Bell's but *without* using proposition (d) above, or anything like it. Specifically, in our 2020 paper [9], we proposed an experiment that, if it were to work as expected (by most physicists), would falsify the conjunction of just propositions (a,b,c) together. That is, our theorem is strictly stronger than Bell's theorem. The "easy way out", of rejecting hidden variables, no longer works. There is no proposition that "standard quantum theory" clearly rejects. Reality is constrained to be even stranger than Bell's theorem taught us.

The key to the thought-experiment in our theorem is the ability to reverse a measurement. Our co-workers at Griffith performed an actual experiment doing this, and saw violations of the new inequalities we derived

[9]. But we called this only a "microscopic proof-of-principle experiment", because there is no generally agreed criterion for a physical process or system to constitute a measurement or outcome, and, I suspect, most physicists would find the simple processes and tiny systems we employed unconvincing.

This is where proposition (c') comes in again. It gives a relatively unambiguous criterion for an outcome (here, elevated to an 'observation') to be absolutely real. Thus, ruling out (a,b,c') is, in my view, the most convincing way to rule out (a,b,c). But an experiment disproving the conjunction (a,b,c') would require technology far beyond that of today. As set out in detail in [10], it would need human-level artificial intelligence, and universal quantum computing at staggeringly large scale and speed. This would enable an intelligent party to observe half of an entangled pair of particles, thereby becoming entangled with a distant particle, while being run on a quantum computer that can be reversed, undoing the observation. See Fig. 2.

The experiment we envisage in [10] is much more difficult than the Heisenberg-limited laser experiment mentioned in the first half above. I do not expect it to be achieved in my lifetime, as it will likely take many decades of technological advancement. But I hope that our theorem is sufficient motivation for future generations of experimentalists to attempt that goal.

There is, I think, a small, but by no means negligible, possibility that an experiment with an artificially intelligent quantum computer would not give the results expected from standard quantum mechanics. If we, the scientific community, are lucky enough that this possibility is an actuality, then at some stage on the path towards that ultimate experiment we may well see deviations from expected behaviour. This, I hope, will motivate the current generation of experimentalists to begin the challenging trek along that path.

Acknowledgements

The recent work described here was supported by the Australian Research Council through Discovery Project grants DP170101734 and DP220101602, and the Centre of Excellence grant CE170100012 (Centre for Quantum Computation and Communication Technology), and by the grant FQXi-RFP-CPW-2019 from the Foundational Questions Institute and Fetzer Franklin Fund. I am grateful to my collaborator, Eric Cavalcanti, for feedback on the "Implications" section of this article. Finally, I would like to thank my PhD supervisor and long-time mentor, Gerard Milburn, for nominating me for the Boas Medal, and all my co-workers on the research for which it was awarded.

About the author

Howard Wiseman is an Australian theoretical quantum physicist. He is best known for his work in quantum control (manipulating matter and information at the quantum scale) and quantum foundations (trying to understand what is really going on when we do this). He is less known for his work in Arthurian history and literature. Howard has won several medals and prizes in Australia, but only for his physics research. He has been elected a Fellow of the Australian Academy of Science, the American Physical Society, and the Optical Society of America (Optica). He has been Director of the Centre for Quantum Dynamics at Griffith University since 2007.

References

[1] S. Daryanoosh, S. Slussarenko, D. W. Berry, H. M. Wiseman, and G. J. Pryde, "Experimental optical phase measurement approaching the exact Heisenberg limit", Nature Communications 9, 4606 (2018).

[2] L. S. Martin, W. P. Livingston, S. Hacohen-Gourgy, H. M. Wiseman, and I. Siddiqi, "Implementation of a canonical phase measurement with quantum feedback", Nature Physics 16, 1046–1049 (2020).

[3] T. J. Baker, S. N. Saadatmand, D. W. Berry, and H. M. Wiseman, "The Heisenberg limit for laser coherence", Nature Physics 17, 179–183 (2021).

[4] A. Schawlow and C. Townes, "Infrared and Optical Masers", Phys. Rev. 112, 1940 (1958).

[5] C. Liu, M. Mucci, X. Cao, G. Dutt, M. Hatridge, and D. Pekker, "Proposal for a Continuous Wave Laser with Linewidth well below the Standard Quantum Limit", Nat. Commun. 12, 5620 (2021).

[6] J. S. Bell, "On the Einstein-Podolsky-Rosen paradox", Physics (New York) 1, 195 (1964).

[7] H. M. Wiseman, "Bell's theorem still reverberates" Nature 510, 467–469 (2014).

[8] Č. Brukner. "A no-go theorem for observer-independent facts". Entropy 20, 350 (2018).

[9] K.-W. Bong, A. Utreras-Alarcón, F. Ghafari, Y.-C. Liang, N. Tischler, E. G. Cavalcanti, G. J. Pryde, and H. M. Wiseman, "A strong no-go theorem on the Wigner's friend paradox", Nature Physics 16, 1199–1205 (2020).

[10] H. M. Wiseman, E. G. Cavalcanti, and E. G. Rieffel, "A 'thoughtful' Local Friendliness no-go theorem: a prospective experiment with new assumptions to suit", arXiv:2209.08491