Preface

The subject of Quantum Measurements has seen an explosive growth both in interest, and in importance, over the recent decades. While internationally there are frequent meetings devoted entirely to it, in India, so far, there have not been any except perhaps for a small discussion meeting in 2009 of about 20 participants on the 'Many Worlds Interpretation' held at the Poornaprajna Institute of Scientific Research (PPISR), Bangalore. To make a beginning, the Centre for Quantum Information and Quantum Computing (CQIQC) at the Indian Institute of Science, Bengaluru, decided to hold a discussion meeting entirely focused on Quantum Measurements.

CQIQC is a Department of Science and Technology (Govt of India) sponsored project which got completed in July 2015. Its primary objective was to bring both theoretical and experimental activities in Quantum Information, Quantum Computing as well as Foundations of Quantum Mechanics of the Institute under one roof. It ran a very successful series of seminars and colloquia. It organized an international conference in January 2013 as well as a satellite meeting for the 13th Asian Quantum Information Science Conference in September 2013. Additionally, it conducted two summer schools in 2012 and 2013.

The discussion meeting on Quantum Measurements took place during 22–24 October 2014. International and national experts as well as many students from all over the country participated in an intense and informed discussion on practically all important aspects of the subject. What was novel to this meeting was that both experimental and theoretical sides of these aspects were represented. The broad range of topics discussed were: (i) varieties of quantum measurements that included Weak measurements, Weak-value measurements, Protective measurements, Arthurs–Kelly measurements of mutually incompatible observables, Quantum non-demolition measurements, and, Ancilla-based quantum measurements; (ii) various aspects of uncertainty relations and beyond that included in-depth discussions of the so called error-disturbance relations, entropic uncertainty relations, etc.; (iii) the classical-quantum divide with emphasis on the so called Macrorealism, and, finally, (iv) Decoherence. This special section consists of selected talks from the discussion meeting (unfortunately we did not get all the manuscripts we would have liked to see in this issue).

The topics that were chosen for discussion at the meeting closely mirrored the exciting and revolutionary developments in uncovering the physical interpretation of quantum theory. Even after Heisenberg and Schrödinger had formally completed the development of quantum mechanics, with impressive empirical successes to follow, such an interpretation of the theory remained obscure. Though Bohr's correspondence principle helped somewhat, it was not adequate to provide a consistent picture. A watershed development in 1927, two years after the formal completions in 1925 by Heisenberg and Schrödinger, was Heisenberg's uncertainty relations, and Bohr's recognition of the centrality of Measurements in arriving at a consistent physical interpretation of quantum theory. Heisenberg's initial paper on the uncertainty relations had several lacunae, the most important, as presciently clarified by Bohr, were his confusing the recoil experienced by the particle with uncertainty, and the absence of the dual aspects of waves and particles in his analysis. Bohr pointed out that by accurately measuring the momentum of the scattered photon, one could completely account for the recoil with complete certainty. Bohr further pointed out that every stage of the measurement has to be carefully scrutinized and that a complete picture can only be obtained by employing both the wave and the particle aspects of quantum systems. Despite these criticisms Bohr accepted the essential correctness of the uncertainty principle. Heisenberg acknowledges by adding a lengthy addendum to his paper. Bohr presented a systematic elaboration of these ideas in the now famous Como meeting in 1927 which can rightly be seen as the birth of Bohr's Complementarity principle, as well as that of the theory of quantum measurements. These ideas played a central role in the famous Bohr–Einstein dialogues on the meaning of quantum theory.

The Heisenberg analysis of his famous 'microscope' gedanken experiment was essentially semi-classical. The central conclusion of that analysis $\delta p \cdot \delta q \simeq h$ for the product of 'errors' in the simultaneous measurement of the two incompatible observables p, q is of a fundamentally different nature than the more familiar $\Delta p \cdot \Delta q \geq \hbar/2$. While the former was in the context of a single measurement, the latter refers to the statistical outcome of an ensemble of measurements when the incompatible observables are measured separately on distinct subensembles as elaborated by von Neumann in his classic *The Mathematical Foundations of Quantum Mechanics*. The second form, being formulated in terms of variances, cannot in general capture either the correct notion of errors when incompatible observables are simultaneously measured. Nor can it capture the notion of a *disturbance* on the measurement of one observable arising out of the measurement of another. In a seminal development pioneered by him, Ozawa (**page 2006)** has shown that the *error–disturbance* relation attributable to Heisenberg can indeed be violated and has shown how to go 'beyond' the Heisenberg relations. Apart from their significance to the foundational aspects of quantum theory, his results have deep ramifications in practice too. The notions of *quantum limits* to achievable sensitivities in experiments based on the Heisenberg relations will all have to be revised.

These new versions of the error-disturbance relations (EDR) have been verified experimentally. Hasegawa (**page 1972**), has, in this special section described their experiments in detail. While Hasegawa's experiments are done with neutrons, Edamatsu (whose manuscript could not be obtained for this special section) uses weak measurements on single photons. Both of them found that the original EDRs can be violated and that their new forms are vindicated. Hasegawa also discusses other experiments central to foundations of quantum mechanics such as neutron-optical weak-value measurements, the Quantum Cheshire-cat and experiments on contextuality in quantum mechanics.

While the uncertainty relations originally due to Heisenberg, and as extended by Ozawa and others essentially involve the second moments of the probability distributions for outcomes, the so called *entropic uncertainty relations* characterize the distributions themselves, and consequently can be much more powerful. The essence of uncertainty relations being the incompatibility of certain observables, one can expect these forms of uncertainty relations to provide stronger characterizations of incompatibility. Prabha Mandayam and Srinivas (**page 1997**) discuss a class of such measures. They also discuss (**page 2044**) how entropic methods can be used to prove that disturbances associated with measurements on identically prepared, distinct, ensembles cannot be reduced arbitrarily. Entropic uncertainty relations, in the context of unsharp measurements of incompatible observables, were also the focus of the contribution by Karthik *et al.* (**page 2061**). They give an overview of such measurements along with results on how presence of quantum memory can significantly strengthen the entropic uncertainty relations.

An explicit model for such unsharp simultaneous measurement of position and momentum was given long ago (1965) by Arthurs and Kelly, who essentially extended the well known von Neumann Measurement Model to this class of measurements. Unfortunately, they chose to publish their results in the not so accessible *Bell System Technical Journal*! Roy (**page 2029**) has given a detailed review of the Arthurs–Kelly measurements. As applications he shows how bounds on von Neumann entropy, various forms of Wigner distributions, noiseless tracking of conjugate variables, remote tomography, etc. can all be obtained. It would be interesting to revisit many results presented in this issue on incompatible observables and their measurements in the specific context of Arthurs–Kelly model.

Another aspect of the measurement to which Bohr stuck to rather vehemantly was with regard to the nature of the measuring apparatus. He maintained that nothing short of a fully classical description of the apparatus would make any sense. This is in sharp contrast to the stand adopted by von Neumann, who treated the measuring apparatus also as a quantum system. Proponents of his view argue that since the constituents of every apparatus are also the very same elementary systems whose successful description requires quantum theory, apparatuses too should be describable quantum mechanically. The issue is technically complex and the verdict is still not out. In the meanwhile there have been intense discussions about the so called classical–quantum divide and the means of bridging the same. One of the most interesting ideas put forward in this connection is that of Macrorealism by Anthony Leggett and Anupam Garg. Garg (**page 1958**) gives a lucid description of Macrorealism, and an assessment of the experimental tests of this concept. In their original work, Leggett and Garg had formulated certain inequalities which have formed the basis for an experimental vindication of Macrorealism. A key ingredient to all such experimental tests is the realization of the so called Non-invasive measurements. Dipankar Home (**page 1980**) discusses these aspects in detail. Likening these Leggett–Garg inequalities to temporal analogs of the Bell's inequalities, he dwells on the use of the so called Negative Result Measurements as means of realizing non-invasive measurements. Besides providing a Wigner-form of the Legget–Garg inequalities, he also discusses the ramifications concerning unsharp measurements, as well as connections to quantum key distributions.

Non-invasive measurements have also been discussed in the experimental work of Mahesh *et al.* (**page 1987**) They advance the general theme of *ancilla-based* quantum measurements, and claim to have realized non-invasive measurements as part of these general strategies. In an earlier work they too had provided experimental tests of the Leggett–Garg inequalities. All these are based on NMR-techniques. Additionally, they have used their protocols to perform various aspects of tomography as well as what they call 'quantum noise engineering'. It remains to be seen as to how non-invasive many of the proposals really are.

While the non-invasive measurements alluded to so far aim to minimize the disturbance of a state due to measurements performed on it, for quite sometime there has been interest in another class of measurement which can also be considered non-invasive in a sense. These are the so called Quantum Non-Demolition Measurements (QND), developed in the context of detection of gravitational waves. Unnikrishnan (**page 2052**) has given a review of this class of measurements. These are also sometimes called Back-action Evading measurements. For example, a measurement of position could induce an uncertainty in momentum which can feed back into the accuracy of position measurement. QND measurements are designed to avoid such a back reaction. After reviewing the basic concepts and formalism, he discusses applications to quantum optics, gravitational wave detection, as well as to spin-magnetometry.

According to the standard lore of quantum measurements, projective measurements on a single member of an ensemble of unknown states has no statistical significance. This is due to the fact that the outcomes of such measurements are random. Aharonov and Vaidman proposed a remarkable measurement scheme called 'Protective Measurements' by them. In their ideal version, they too are non-invasive. According to this, a single measurement on a single copy can reveal the expectation value of the measured observable without affecting the state. Then by repeating the process for a complete set of observables, the state can be determined. Qureshi and Hari Dass (**page 2023**) have discussed this interesting measurement scheme and its limitations, particularly the impossiblity of determining the state with certainty owing to entanglements that are inevitable in any practical implementation. They also point out some pragmatic merits of protective measurements.

Aharonov, Vaidman and Albert also proposed another remarkable class of measurements called Weak Measurements. A way to think about these within the von Neumann models is to consider the apparatus as a very broad superposition of pointer states, in contrast to the projective (also called Strong) measurements where the apparatus is prepared in a pointer state. The novelty of these classes of measurements is that each weak measurement has almost negligible disturbance on the state. But the price one pays is that the ensemble sizes required for comparable levels of errors are extremely large, else the errors are too big. Another equally interesting variant is the so called Weak-value measurement; this consists of a weak measurement followed by what Aharonov and coworkers call a Post-selection implemented through a projective measurement and selecting only prescribed outcomes. The outcomes of weak-value measurements are suitably normalized matrix elements of the observable. These are in general complex, and separate weak measurements are necessary for their real and imaginary parts. The fact that weak values can be larger than the largest eigenvalue has been much sensationalized, starting from the provocative title 'How the result of a measurement of a component of the spin of a spin-1/2 particle can turn out to be 100' by the authors themselves. As such there is nothing in quantum theory that requires these normalized matrix elements to be bounded by the eigenvalues of the observables. One of the spin-offs of these measurements is that small signals can be amplified. The fact that their disturbance of the state is negligible has also been cited as the reason for considering weak measurements to be ideal candidates for non-invasive measurements.

Over the last few years weak measurements and weak-value measurements (some people refer to the latter as also Weak measurements, which is a very confusing nomenclature) have dominated both experimental as well as theoretical discussions of quantum measurements, and the discussions at the meeting reflected this trend. Pragya Shukla (**page 2039**) focuses on situations when the outcome of a weak-measurement (she really has weak-value measurement in her mind) lies outside the range of eigenvalues, which she calls *superweak* and interprets this as a 'supershift' on the measuring device owing to a 'coherent superposition of waves'. She has likened them to the oscillations in a band-limited function faster than the maximum frequency over arbitrarily large intervals. Another interesting feature discussed by her is the universality in the distribution of weak-values. Satya Sainadh *et al.* (**page 2002**) theoretically analyse elastic scattering in resonance fluoroscence as a manifestation of weak-value amplification. They make the interesting point that such amplifications can be quite generally understood from the Wigner–-Weisskopf theory of spontaneous emission. Patrick Das Gupta (**page 1946**), in a presentation somewhat disconnected from the concerns of quantum measurements, discusses the effect of mutual gravitational interaction between ultra-cold gas atoms on the dynamics of Bose–Einstein condensates.

Hasegawa also presents an interesting experimental application of weak-value measurements to the so called Quantum Cheshire Cat wherein he claims to have separated spin and momentum of neutrons along different paths of a neutron interferometer. Tanay Roy *et al.* (**page 2069**) present high precision and highly controllable experiments on various aspects of weak measurements using superconducting qubits. They are able to smoothly go over from regimes of strong (projective) measurements to those of weak measurements. In the former they can exhibit the so called Quantum Jumps, while in the latter they can exhibit the characteristic stochastic trajectories. They achieve all this in real time. Superconducting qubits promise to be among the best candidates for high-precision experimental probes of quantum measurements.

It has been found useful to enlarge the notion of quantum evolutions to include measurements also. Apoorva Patel and Parveen Kumar (**page 2017**) discuss an evolutionary formalism to describe both projective and weak measurements. They raise several interesting questions regarding the role of the Born interpretation and also on the desirability to design suitable experiments to throw light on such evolutions. Debmalya Das and Arvind (**page 1939**) explore the tomographic aspects of weak measurements. They wish to exploit the apparent non-invasiveness of weak measurements to recycle the state. They claim that under certain circumstances their method can outperform state determinations via projective measurements. Hari Dass (**page 1965**) presents three results on weak measurements. The three are (i) a demonstration that repeated weak measurements on a single copy cannot provide any information on the state of the copy, and, they are as invasive as projective measurements; (ii) that weak measurements perform no better than strong measurements as candidates for non-invasive measurements in testing the macrorealism inequalities of Leggett and Garg, and, (iii) weak-value measurements are optimal in the sense of Wooters and Fields when the post-selected states are *mutually unbiased* with respect to the eigenstates of the measured observable. As part of (i) he explicitly constructs the stochastic trajectory during a weak measurement. It is important to connect this to the experimental results of Tanay Roy *et al.* as well as the evolutionary formalism of Apoorva Patel and Parveen Kumar.

Finally, we turn to one of the most vexing aspects of quantum measurements, namely, the nature of the apparatus. As already mentioned, Bohr's take on this was orthogonal to that of von Neumann and to most of current ideas. He insisted that the apparatus had to be classical. In the opposite view point the apparatus is still a quantum system, albeit highly complex, and the hope is that this complexity leads to an effectively classical behaviour. Though reasonable sounding, to this day there is no completely satisfactory derivation, or even approximate derivation of this 'hope'. No matter which of the many measurement schemes one considers, there is always a point at which the strong or projective measurements have to be invoked. This always leads to an entangled superposition of all possible system-apparatus correlated states, and not the single outcome associated with a successful measurement. The present thinking on this is that an apparatus–environment interaction decoheres this superposition to give rise to the seemingly classical outcome. The pointer states are also picked out by this interaction as the basis in which the mixed density matrix becomes diagonal. A big challenge is to vindicate this decoherence picture in a more systematic manner. Sushanta Dattagupta (**page 1951**) discusses many aspects of decoherence as well as coherence in quantum systems from a condensed matter perspective.

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