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Quantum mechanics and the science of measurements

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Abstract. — The accuracies of measurements of almost all fundamental physical constants have increased by factors of about 10,000 during the past 60 years. Although some of the improvements are due to greater care, most are due to new techniques based on quantum mechanics. In popular accounts of quantum mechanics, such great emphases is placed on the Heisenberg Uncertainty Principle that it often appears that the primary effect of quantum mechanics should be to diminish measurement accuracy whereas in most cases it is the validity of quantum mechanics that makes possible the vastly improved measurement accuracies. Seven quantum features that have a profound influence on the science of measurements are: (1) Existence of discrete quantum states of energy $E_j$. (2) Energy conservation in transitions between two states. (3) Electromagnetic radiation of frequency $\nu$ is quantized with energy $\hbar \nu$ per quantum. (4) The identity principle. (5) The Heisenberg Uncertainty Principle. (6) Addition of probability amplitudes (not probabilities) so $P = |\psi_1 + \psi_2|^2 \neq |\psi_1|^2 + |\psi_2|^2$. (7) Wave and coherent phase phenomena. Of these seven quantum features, only the Heisenberg Uncertainty Principle limits the accuracy of measurements, and its effect is often negligibly small. The other six features make possible much more accurate measurements of quantum systems than with almost all classical systems and the identity principle provides meaning and significance to highly precise measurements with quantized systems. These effects are discussed and illustrated.

Introduction.

It is a pleasure to write an article in honor of Professor Pierre Jacquinot, who has directed a laboratory in which so many accurate measurements have been made and who has participated in so many beautiful experiments himself over the past sixty years. A discussion of quantum mechanics and the science of measurements is particularly appropriate since he has contributed so much to the subject himself.

In popular accounts of quantum mechanics, such great stress is ordinarily placed on the Heisenberg Uncertainty Principle that many people assume that quantum phenomena only lead to inaccuracies in fundamental physical measurements. Although that great principle does indeed imply fundamental limitations, the Heisenberg uncertainties are often so small as to be
unimportant and, at the same time, other quantum features allow measurements of far greater accuracy than would be possible in an unquantized world.

Characteristic quantum features.

Seven features of quantum mechanics which exert profound influences on the science of measurement are:

1) The existence of discrete quantum states of energy $W_i$.
2) When a system makes a transition between two states, energy is conserved.
3) Electromagnetic radiation of frequency $\nu$ is quantized with energy $h\nu$ per quantum where $h$ is the Planck constant.
4) The identity principle.
5) The Heisenberg Uncertainty Principle
6) Addition of probability amplitudes instead of probabilities. $\left[P = |\psi_1 + \psi_2|^2 \neq P_1 + P_2\right]$. 
7) Wave and coherent phase phenomena.

A quantum mechanical system can exist in certain specific energy states $W_1, W_2, \ldots W_n$ and in many cases these energy states are discrete. When such a system makes a transition between on such discrete states and another, energy is conserved. From the second and third of the above features, the emitted photon in such a transition has the energy $h\nu$ given by

$$h\nu = W_f - W_i$$  \hspace{1cm} (1)

The existence of such discrete frequencies permits accurate measurements and accurate frequency standards that simply would not be possible of the allowed frequencies had the continuous distribution that characterizes a classical system.

The meaning of the identity of two particles in quantum mechanics is far more profound that the normal meaning of the word identical. I am the father of identical twin daughters, and indeed they are remarkably alike. Nevertheless, when one speaks of two protons or two hydrogen atoms as being identical, much more is meant. For example, one can test the identity of two particles by scattering one from another; there is a marked difference in the observable scattering if the particles are truly identical instead of being almost identical. The identity principle has a profound effect on the science of measurements. For example, it provides assurance that the frequency of a cesium atom beam standard will be the same for cesium which comes from Britain or from United States. The identity principle also adds much to the significance and universality of accurate physical measurements. With the quantum assurance that sufficiently similar atoms are identical, a scientist measuring an atomic property on the earth knows that the result of his measurement would be applicable to a scientist on the moon as well. In contrast, an accurate geological measurement on the earth does little to determine the geology of the moon. The lack of an identity principle in geology accounts for the difference.

A guiding principle in the early development of quantum mechanics was the Heisenberg Uncertainty Principle which emphasizes certain quantum limitations on precision measurements. For example, if the energy $W$ of a system is measured to an accuracy $\Delta W$ then there must be an uncertainty $\Delta t$ as to the length of time it is in the energy state $W$, where

$$\Delta W \Delta t \geq h/4\pi$$  \hspace{1cm} (2)

Although the uncertainty principle limits the accuracy to which two complementary variables can be measured, Planck's constant $h$ is fortunately small, so remarkably accurate measurements
are possible. The world of precision measurement would be far different if \( h \) were \( 6.6 \times 10^{-34} \) J \( \cdot \) s instead of \( 6.6 \times 10^{-34} \) J \( \cdot \) s (the world itself would also be far different in that case). Although, the Heisenberg Uncertainty Principle can seriously restrict the accuracy of measurement on a short lived particle or of an atomic state whose mean life is \( 10^{-8} \) s, there are states with such long natural lifetimes that the uncertainty due to spontaneous decay is negligible; a one day mean life, for example, would give a \( 10^{-6} \) Hz resonance width.

The limitations of the Heidelsberg Uncertainty principle are further diminished in that they apply to a single measurement on a single system. If \( N \) different systems are measured, the uncertainty in principle is reduced by \( \sqrt{N} \). For example, within less than 10 seconds we can easily detect a shift of one part in \( 10^{14} \) in a \( 10^9 \) Hz hydrogen maser oscillator even though the Heisenberg uncertainty limit for a single atom is \( 0.1 \) Hz or one part in \( 10^{10} \). The reason we can do this so accurately is that within 10 seconds we are making measurements on \( 10^{13} \) atoms so the effective measurement limit in principle is \( 3 \times 10^6 \) lower than that for a single atom.

Furthermore, in some cases when the width of a resonance is determined by the Heisenberg Uncertainty Principle, it is possible – at a sacrifice in intensity – to obtain a significantly narrower resonance by making observations only on those systems which have lived a longer time than the average [1].

The valid restrictions from the Heisenberg Uncertainty Principle are often exaggerated and greater precision than that suggested by the false limit can be obtained by interpreting the principle correctly. For example, in quantum electrodynamics, the Heisenberg Uncertainty Principle sets a lower limit to the product \( \Delta X_1 \times \Delta X_2 \) of the uncertainties of the amplitudes \( X \) of the two quadrature phases of the field.

This does not mean that each uncertainty is equal to the square root of the uncertainty of the product. One of the uncertainties can be greatly diminished if the other is allowed to increase correspondingly. This procedure, when applied to optics, is often called “squeezed light” and, when applied to mechanical oscillators, is called a “quantum non-demolition measurement”.

The wave nature of the quantum mechanical state function and the possibilities of coherent effects with such coherent waves provide many different devices for precision measurements such as interferometers, masers and lasers. Furthermore, the energy gap that results from electron pairing in superconductors provides coherency effects on a macroscopic scale. The coherent waves of electron pairs, for example, give rise to the remarkable phenomenon of zero electrical resistance in superconductor. As a consequence of coherency on a macroscopic scale, the magnetic flux enclosed by a superconducting ring must be limited to an integral multiple of the flux quantum

\[
\phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15} \text{ Wb.}
\]

The same coherency gives rise to the remarkable Josephson effects [2] when a thin barrier, through which the electron pairs can quantum mechanically tunnel, is placed between two superconductors. If, for example, there is a voltage \( V \) across such a Josephson junction the electron pairs will change energy by \( 2 \) eV in crossing the junction and the current through the junction will be accompanied by an oscillatory current whose frequency satisfies the usual quantum relation of equation (1). Alternatively, if microwaves of frequency \( \nu \) are coupled to the Josephson junction, abrupt steps will appear in the current versus voltage curve whenever

\[
\nu \ h n = 2 \ eV
\]

where \( n \) is an integer. So far this relation seems to be exact and permits accurate measurements of voltages in terms of frequencies. The factor relating frequency to voltage is approximately 484 megahertz per microvolt. Another quantum discovery which contribute to precision measurements is the quantized Hall effect which occurs at low temperatures when an electric field
and a strong perpendicular magnetic field are applied to a semiconductor. The ratio of the current induced at right angles to both fields to the strength of the electric field (the Hall conductance) is then quantized in integral [3] or proper fractional [4] multiples of $e^2/h$ as shown by Von Klitzing and his associates.

If we now return to the seven characteristic quantum features we see that only one – the Heisenberg Uncertainty Principle – provides a limitation to the accuracy of measurement and that this limitation is often so low as not to be serious The other six characteristics give universality and significance to accurate measurements that are orders of magnitude more accurate than would be possible in a purely classical world. This was vividly brought to my attention by the difficulty I once had in having a slide made which reported some of my measurements with an accuracy of part in $10^{14}$. The engineer who was asked to prepare the slide at first refused on the grounds that he had been trained as an engineer and from the point of view of an engineer it was utterly meaningless to express any physical number with such ridiculously high accuracy. As a classical engineer he was quite right. To express the height of the Tour Eiffel to an accuracy of one part in $10^{14}$ would be utterly meaningless – its height can’t be defined to that accuracy and it changes more than that from second to second as it blows in the wind and thermally expands. However, in a quantized world such accurate measurements are both meaningful and possible.

Although most accurate measurements depend on quantum properties, there is no fundamental principle that precludes accurate classical measurements, as is currently illustrated by recent fascinating results from comparisons of highly stable atomic clocks with certain millisecond pulsars. Although most pulsars are less stable than atomic clocks, in a few cases pulsars may rival or exceed the stability of laboratory atomic clocks. For one binary pulsar, the observed changes of the orbital period of the binary can be attributed to the loss of energy by the radiation of gravity waves.

Applications to measurements.

A particularly beautiful illustration of modern measurement is the determination of the magnetic moment $\mu_e$ of the electron in terms of the Bohr magneton $\mu_B$ by Dehmelt and his associates [5]. Using a single electron in the magnetic field of a Penning trap and observing $g - 2$ in a magnetic resonance experiment, they find:

$$\frac{\mu_e}{\mu_B} = 1.001159652193(10) \times 10^{-5} \text{ ppm}.$$  

It is of interest to note that the best theoretical value for this by the quantum electrodynamics calculation of Kinoshita [6] is $1.001159652140(26)$.

There are many examples of the pervasive dependence of modern precision measurements on quantum mechanics. The unit of time is defined in terms of the transition frequency between two specific hyperfine states of the cesium atom. The unit of length is in turn defined in terms of the distance travelled by light in a specific time. Quantum devices, such as laser interferometers, are often used for practical measurements. Magnetic fields are measured by observing the electron magnetic resonance frequency or by using superconducting quantum interference devices (SQUIDS) based on the Josephson effect. Since January of 1990 the international unit of voltage has been represented in terms of the Josephson frequency and the unit of resistance in terms of the quantized Hall effect.

Most of the fundamental constants such as $\alpha$, $e$, $\hbar$, etc. now come from a least squares analysis of the results of physical measurements on a large number of physical quantities which involve the different fundamental constants in a variety of quantum relations. Although this leads to
much better values for the constants, the procedure is conceptually complicated: no longer
can one simply say that the charge of the electron comes from measurements on charged
oil drops in electric fields. A further disadvantage is that new values of the fundamental
constants usually must await a full analysis of all relevant data, usually under the auspices of
an international committee. A single new measurement may change the adjusted values of a
number of fundamental constants so one must be cautious in using the values of a previous full
adjustment in combination with the results of more recent experiments.
The increased precision offered by the present quantum based measurement of the fundamental
constants can best be seen by comparing the results of the 1929 evaluation of the fundamental
constants with those of the CODATA 1987 evaluation [7]. In 1929 the estimated error for
most fundamental constants was about 1000 parts per million. Comparisons with later more
accurate measurements show that most of these estimated errors were too optimistic by a
factor of about 7, so the actual errors were about 7000 parts per million. The proposed 1986
evaluations have estimated errors that in many cases are better than 0.1 parts per million and
in most cases better than 0.7 per million. If these new estimates of error are realistic, there has
been an improvement in accuracy by a factor of about 10,000 between 1929 and the present.
Most of this improvement has come from combinations of quantum based measurements. This
is well illustrated by the observation that the one estimated error which is the largest and
has diminished the least since 1929 is that for $G$, the only constant not associated with a
quantum measurement. The estimated error for $G$ in the latest evaluation is $1.1 \times 10^{-4}$ which
is only 6 times better than that of the 1929 evaluation. Clearly a quantum theory of gravity
with experimentally measurable values is required if $G$ is to be determined 100 times more
accurately to match the precision of the other fundamental constants whose values come from
quantum measurements.

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