Chapter 12
Entanglement and Experimental Tests of Quantum Mechanics

Equations (7.3)–(7.6) display two possible features appearing in the description of bipartite systems: in the first two equations, each subsystem possesses its own quantum state φ_p, which constitutes a complete description of the physical state of the subsystem (a familiar situation from classical physics). This feature of separability does not hold for the last two equations. Schrödinger was the first to emphasize the non-classical features of "entangled" states and coined this term in [76].

Alain Aspect describes the difference between classical and quantum correlations in bipartite systems as follows: "If we have a pair of identical twins we do not know what their blood type is before testing them, but if we determine the type of one, we know for sure that the other is the same type. We explain this by the fact that they were born with, and still carry along, the same specific chromosomes that determine their blood type. Two entangled photons are not two distinct systems carrying identical copies of the same parameter. A pair of entangled photons must instead be considered as a single, inseparable system, described by a global wave function that cannot be factorized into single photon states." [77].

The concept of entanglement is a direct consequence of the superposition principle applied to composite systems. It has become a fundamental tool in the solution of many quantum problems during the second half of the last century:

- In the discussions on the validity of quantum mechanics [Sect. 12.3, including the clarification of the EPR paradox (Sect. 12.3.2)].
- In the field of quantum information (Chap. 13).
- In the description of the emergence of the classical world from the quantum substrate and, as a consequence, in a consistent quantum explanation of the collapse postulate (Sect. 14.3†).

We also discuss in the present chapter some recent experiments confirming the validity of quantum mechanics (Sect. 12.3), all of which make use of the concept of entanglement.

Entanglement constitutes the central tool in the forthcoming chapters. In all presentations we make use of two-dimensional Hilbert spaces. Therefore the considerations on these spaces given in Sects. 3.2 and 5.2.2 are assumed here. In

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particular, a set of basis states for a single qubit is given by the two-component column vector representation

$$\varphi_0 = \begin{pmatrix} 1 \\ 0 \end{pmatrix}; \qquad \varphi_1 = \begin{pmatrix} 0 \\ 1 \end{pmatrix}. \tag{12.1}$$

Qubits are realized either by means of particles with spin $s = \frac{1}{2}$, two isolated levels, the two states of photon polarization (Sect. 9.8.2†), etc. It is yet unclear which is better for computational purposes, although photons are preferred in the case of communication.

The quantum formalism to be used from here on is rather different from the one that we have employed so far. For instance, the matrix density formulation of quantum mechanics (Sect. 14.4) is a convenient tool to deal with entangled states, and to depart from the considerations of isolated microsystems.

12.1 Entanglement

Let us perform some thought experiments with the same filters used in Sect. 2.5.1: two particles, 1 and 2, are emitted simultaneously from the same source, in opposite directions (Fig. 12.1). Each particle enters a filter aligned with the laboratory z-axis and may be detected by an observer provided with another filter. The same orientation β, relative to the laboratory frame, holds for both observers' filters. The down channel is blocked in all four filters. Thus $\cos^2(\beta/2)$ represents the probability that a particle is detected, and $\sin^2(\beta/2)$ the probability that it gets absorbed (5.25).

If two particles are emitted in the entangled state

$$\frac{1}{\sqrt{2}}\left[\varphi_0(1)\varphi_0(2) + \varphi_1(1)\varphi_1(2)\right], \tag{12.2}$$

then:

- A measurement of particle 1 destroys the entangled state. Particle 2 assumes the same state as the one into which particle 1 was projected by the measurement.
- The correlation is 100%, regardless of the filter orientation β.

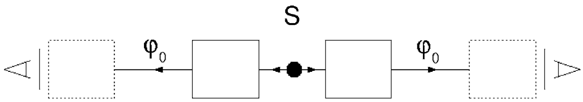

Fig. 12.1 Thought experiments illustrating the properties of entangled states. Both particles are filtered by the source filters into the state φ_0 through a first filter (*full line box*) and are detected by filters oriented at an angle β (*dashed box*). Trajectories inside the filters have not been drawn

- This result is also independent of the initial direction of the z-axis. Replacing φ_0, φ_1 by linear orthonormal combinations χ_0, χ_1 generated by rotations around the y-axis, yields the entangled state

$$\frac{1}{\sqrt{2}}\left[\chi_0(1)\chi_0(2) + \chi_1(1)\chi_1(2)\right].$$

  A measurement of particle 1 would project particle 2 into the same state as particle 1.
- The comparison with the (non-entangled) product state $\varphi_0(1)\varphi_0(2)$ is illuminating: here the probability that the two particles get through is $\cos^4(\beta/2)$, while the probability that both are absorbed is $\sin^4(\beta/2)$. Therefore the probability that both observers find the same result is $1 - (1/2)\sin^2\beta$. If $\beta = \pi/2$, this last probability has the value 1/2, the same classical value as for two independent players tossing coins.
- The correlation implicit in (12.2) takes place regardless of the distance between the two particles: particle 2 (non-locally) becomes represented by a definite state as the result of the measurement of particle 1. Entanglement implies that nature is non-local, since the outcome of the local measurement on the second particle is determined by quantum correlations encoded in the total, entangled state of the bipartite system.
- Note that the outcome of the measurement on the first particle is completely random. This randomness implies that any useful information between the two partners has to be transmitted by conventional means. Therefore, although quantum mechanics is a non-relativistic theory, its probabilistic structure prevents any contradiction with relativity theory.

Entanglement constitutes a profound, non-classical correlation between two (or more) quantum entities. The constituent parts of entangled systems do not have their own individual quantum states. Only the total system is in a well-defined state. This is fundamentally unlike anything in classical physics.

12.2 The Bell States

A complete set of basis states for the two-spin system may be either constructed as products of the states (12.1), or represented by four component column vectors

$$\varphi_0^{(2)} = \varphi_0\varphi_0 = \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}; \quad \varphi_1^{(2)} = \varphi_0\varphi_1 = \begin{pmatrix} 0 \\ 1 \\ 0 \\ 0 \end{pmatrix},$$

$$\varphi_2^{(2)} = \varphi_1\varphi_0 = \begin{pmatrix} 0 \\ 0 \\ 1 \\ 0 \end{pmatrix}; \quad \varphi_3^{(2)} = \varphi_1\varphi_1 = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}. \tag{12.3}$$

It is customary to think of the first qubit in the product representation as the control qubit, and the second as the target qubit.

A general state is written as the superposition

$$\Psi_c^{(2)} = \frac{1}{\sqrt{|c_{00}|^2 + |c_{01}|^2 + |c_{10}|^2 + |c_{11}|^2}} \begin{pmatrix} c_{00} \\ c_{01} \\ c_{10} \\ c_{11} \end{pmatrix}. \tag{12.4}$$

The Bell states constitute specific examples of entangled pairs

$$\varphi_{B_0} \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix}, \qquad \varphi_{B_1} \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 0 \\ 0 \\ -1 \end{pmatrix},$$

$$\varphi_{B_2} \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ 1 \\ 0 \end{pmatrix}, \qquad \varphi_{B_3} \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ 1 \\ -1 \\ 0 \end{pmatrix}. \tag{12.5}$$

- Since Bell states are orthonormal, any two-qubit state may be expressed as a linear combination of these states.
- The Bell states are eigenstates of the product operators $\hat{S}_z(1)\hat{S}_z(2)$ and $\hat{S}_x(1)\hat{S}_x(2)$ (see Problem 1). These product operators are included among the interactions in the controlling Hamiltonian (13.14), used to manipulate qubits.
- Successive introduction of these product interactions separates any two-qubit system into the four Bell channels, in a similar way as the interaction with the magnetic field splits the two channels associated with a single qubit (Sects. 2.5.1 and 5.2.1).
- The two spins in a product operator must be simultaneously measured, since detection of a single spin destroys the entanglement. On the contrary, unitary operations can be applied to any one spin or to both of them.

12.3 Experimental Tests of Quantum Mechanics

Thought experiments played a crucial role in the clarification of controversial aspects of quantum mechanics. The discussions between Bohr and Einstein are paradigmatic in this respect (Sect. 15.5.2). However, since the end of the twentieth century, real experiments have replaced thought ones. Not only have earlier views been confirmed, but also more counterintuitive aspects of quantum mechanics have been brought into focus. In this presentation we restrict ourselves to the discussion of three types of experiments, in spite of other fascinating results that have been or are being obtained:

- Two-slit experiments which, according to Feynman constitute "a phenomenon which is impossible, *absolutely* impossible, to explain in any classical way." ([23], p. 1–1).
- Experiments that can decide between local realism or quantum mechanics as the proper tool for describing the physical world.
- Experiments with single quantum systems, which bear on the statistical framework of quantum mechanics.

Entanglement plays a central role in all these experiments. Present sources of entangled photons are based on the process of parametric down conversion: if a non-linear optical crystal is pumped by a laser beam, a photon may decay into two entangled photons (with a small probability, $10^{-12} - 10^{-10}$). The energy and momentum of the two photons add up to their value in the original one. The two photons may have the same or different polarizations.

12.3.1 Two-Slit Experiments Revisited

Two-slit experiments performed with a single qubit are described in Sect. 2.5.2.

The superposition (2.29) giving rise to interference phenomena requires that there is no way to know, even in principle, which path the particle took, a or a'. Interference is destroyed if this information exists, even if it is dispersed in the environment.

Two-slit experiments with two entangled particles have been used to verify even more spectacular and non-intuitive consequences of quantum mechanics.[1]

Consider two photons, A and B, emitted in opposite directions. Photon A is monitored by detector A after going through a double slit with holes at a and a'. Photon B gets across a lens and can be observed by detector B placed at different distances behind the lens (Fig. 12.2). Whenever photon A is found in a beam at a (a'), photon B is in the beam b (b'). The entangled quantum state is

$$\Psi = \frac{1}{\sqrt{2}} \left(\varphi_a(A)\varphi_b(B) + \varphi_{a'}(A)\varphi_{b'}(B)\right) . \qquad (12.6)$$

- If B is not registered, the distribution of A on a plane parallel to the double slit is incoherent. This is due to the fact that we can still obtain information about the path of A by measuring the state of B.

[1] Intensive use has been made of [78], [79].

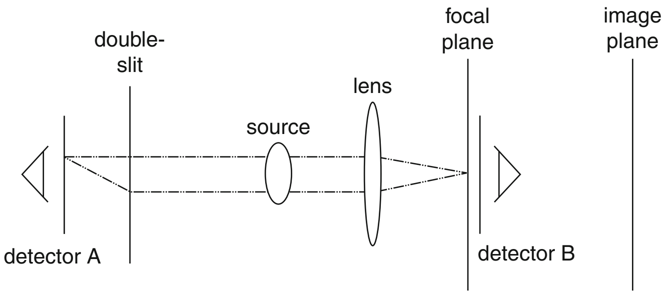

Fig. 12.2 A double-slit diffraction pattern measured with entangled photons. The two photons are detected after the double slit and at the focal plane of the lens, respectively. Detector B may also be displaced towards the image plane

- If photon B is detected at the focal plane of the lens, information about its distance from the propagation axis before the lens is lost, and thus information about through which slit A proceeds is lost as well. The momentum of both photons is well defined and an interference pattern appears behind the two slit plane (wave feature). Photons are collected one by one, and the observed count rate implies that the average spatial distance between photons is at least of the order of 100,000 km.
- One can find through which slit A proceeds through, by detecting B at the image plane (particle feature), since there is a one-to-one relationship between positions on this plane and the double slit. No interference pattern appears in this case.
- Interference pattern and path information are mutually exclusive results. Therefore, Bohr's complementarity (Sect. 15.5.1) appears as a consequence that it is not possible to position detector B simultaneously at the focal and at the image plane. Intermediate situations are also possible, the visibility of the interference pattern being reduced by placing detector B between the focal and the image plane: the experiment displays a continuous complementarity.
- After detection of A, one can arbitrarily delay detection of B, either at the focal or at the image plane. Thus the possibility of detecting or not detecting a diffraction pattern is decided *after* the detection of the diffracted photon. According to this result, it has been claimed that the future can modify the past, in quantum mechanics. However, this interpretation is incorrect, since the prediction of the outcome requires a total specification of the experimental setup, including the position of all detectors (see Bohr's definition of "phenomenon," Sect. 2.4.1).
- Registration of A behind the double slit results in a Fraunhofer double slit pattern for B at the focal point, although B never proceeded through a double slit. This result has been interpreted as a consequence of the fact that the state incident on the double slit is a wave packet with appropriate momentum distribution such that the probability density has a peak at both slits. By virtue of the strong momentum entanglement at the source, B has a related momentum distribution (in fact, it

is the time reversal of the other wave packet) and the Fraunhofer observation conditions become realized after the lens [78].

12.3.2 EPR and Bell Inequalities

We consider a source emitting two particles in the Bell state

$$\varphi_{B_0} = \frac{1}{\sqrt{2}} \left[\varphi_0(1)\varphi_0(2) + \varphi_1(1)\varphi_1(2)\right]. \tag{12.7}$$

If each particle is detected by a Stern–Gerlach detector (Fig. 2.4c) and if the two detectors are oriented along the same direction, particle 2 will be detected in the same spin state as particle 1, independently of their mutual distance. Einstein, Podolsky and Rosen [16] admitted the validity of this quantum prediction, but concluded about the incompleteness of quantum mechanics using the following argument[2]:

- The state of particles exists independently of observation (the notion of physical reality stated in Sect. 2.1).
- A measurement of particle 1 cannot affect the state of particle 2 if they are at sufficient macroscopic distance (notion of locality).

Thus, particle 2 must have carried information about its spin state before detection of particle 1. Therefore, there must be an underlying mechanism – usually called hidden variable – completing quantum mechanics.

In 1964 John Bell realized that local realism, as understood by EPR, was incompatible with quantum mechanics [81]. He devised a thought experiment in which the two fundamental world views would yield different results. Thus physical facts, and not philosophical considerations, could decide between these points of view.

A double Stern–Gerlach apparatus is improved by allowing each of the two detectors to rotate around the beam axis (y-axis). They may be oriented along one of the three directions (Fig. 12.3): along the z-axis (orientation a); making an angle of $2\pi/3$ with it (orientation b); an angle of $4\pi/3$ (orientation c). In the following, the notation (α_1, α_2) labels the position of the detectors 1 and 2, respectively. For instance, (a, c) means that detector 1 points along the z-axis, and detector 2 is oriented at an angle $4\pi/3$ relative to this axis. It is assumed that the orientations of the two detectors are totally uncorrelated. Moreover, no connections between source and detectors or between detectors are allowed.

In the first place, we analyze the problem from the point of view of local realism.[3] The instructions carried by each particle are of the form $x_a x_b x_c$, meaning that if the

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[2]The present argument is the spin version of the EPR original one. The adaptation is due to David Bohm [80].

[3]The Bell inequality described here is taken from [82].

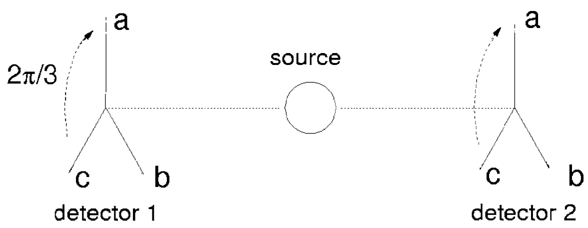

Fig. 12.3 Sketch of an experiment testing the Bell inequality described in the text. At each detector position, the three axes a, b, c lie on the same plane perpendicular to the trajectories

detector is at the jth position ($j = a, b, c$), the result of the measurement is x_j ($x_j = 0, 1$).

There are eight possible sets of instructions, namely: 000, 001, 010, 011, 100, 101, 110, 111. It is unimportant which set is valid during a given run. It is important, however, that the two particles carry the same set, because it is an experimental fact that the same result is obtained for both particles if the two detectors display the same orientation (Bohm-EPR experiment).

Let us exclude for the moment the instruction sets 000 and 111. For any of the remaining six sets, the same results are obtained for both particles in five cases, and opposite results in four cases. For instance, if the instruction set is 011, the pairs (aa),(bb),(bc),(cb),(cc) yield the same result, while opposite results are obtained from (ab),(ac),(ba),(ca).

It is obvious that the two excluded sets of instructions can only increase the possibility that the two counters yield the same result. Therefore, the probability of obtaining the same result must always be $\geq 5/9$ (Bell inequality).

Let us now perform a quantum analysis of the experiment. According to (5.25), the expression of state $\varphi_0^{(a)} = \varphi_0$ in the basis corresponding to the orientations b, c is

$$\varphi_0^{(a)} = \frac{1}{2}\varphi_0^{(b)} + \frac{\sqrt{3}}{2}\varphi_1^{(b)} = -\frac{1}{2}\varphi_0^{(c)} + \frac{\sqrt{3}}{2}\varphi_1^{(c)}. \tag{12.8}$$

Since only the relative angle between the two detectors matters, we can assume without loss of generality that particle 1 has been detected in the state φ_0 with the apparatus in the orientation a. The probabilities of the different outcomes for particle 2 are given in Table 12.1. The sum of probabilities for each orientation divided by the number of orientations yields the same probability for obtaining equal or opposite results, at odds with the prediction of local realism. An identical argument applies if particle 1 was to be detected in the state $\varphi_1^{(a)}$.

At the time of Bell's publication it was not possible to perform an experimental test. In the first successful attempt, spin 1/2 particles were replaced by two photons emitted in a radiative $J = 0 \to J = 0$ cascade using Ca atoms as sources (1981). As expected for entangled photons, the same polarization state was verified for both of them. A Bell inequality somewhat different from the one explained above was

Table 12.1 Probabilities for the results of particle 2

Detector 2	*a*	*b*	*c*	Total probability (%)
Same result as for 1	1	1/4	1/4	50
Opposite result	0	3/4	3/4	50

used. The experiment contradicted the prediction of local realism and confirmed the existence of the quantum correlation [83].

The localization aspect was treated by increasing the distance between the two detectors as far as 13 m, so no signal from one to the other counter could be transmitted at subluminal velocities before detection.

However, two loopholes remained open.[4] One of them consisted of the possibility that the apparatus settings could be known by the detectors and/or by the source before registration of the photons. This loophole was closed by introducing the parametric down conversion (Sect. 12.3), by increasing distances to 355 m and by changing the measurement settings according to a random-number generator in a time scale much shorter than the photon time of flight (1/13). The importance of the last feature stresses the relevance of this experiment [84].

Another logical loophole consisted of the possibility that the detected photons were not faithful representatives of all photons emitted, most of which were lost. This possibility was ruled out by observing nearly all entangled pairs of ions in a cavity [87].

Today it is possible to violate Bell inequalities by many standard deviations in short times. Moreover, in case of Schrödinger cat states with three and four photons (see Sect. 14.2), situations exist in which predictions of quantum mechanics and local realism are exactly the opposite. Experiments have again confirmed the quantum prediction.

12.3.3 Single Quantum Systems

Starting in the 1970s, it became possible to manipulate and observe single quantum objects, such as a photon or an ion. Improvements in the knowledge of certain quantities, such as the gyromagnetic ratio of the electron (Sect. 5.2.2) were obtained through the trapping of an electron on a macroscopic time scale with electric and magnetic fields. It has also been possible to verify the indistinguishability between two electrons or two atoms of the same element, a key fact in quantum physics. Moreover, many thought and counterintuitive experiments became experimentally feasible.

A common feature of the ion and photon trap experiments is that the Jaynes–Cummings model can be applied if the bipartite interacting system (field plus atom) substitutes the quantum oscillator and the two-state system of Sect. 3.4. In this

[4]The two loopholes have not been closed yet in a single experiment.

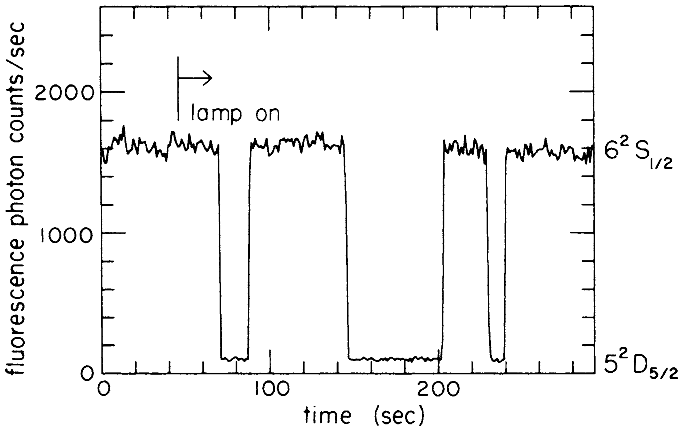

Fig. 12.4 Quantum jumps of a single ion in a trap. (Reprinted with permission from Nagourney et al. [85], with authorization from the American Physical Society)

simple model there appears for the first time the entanglement of a microsystem with a macrosystem[5] (3.53). Note, however, that the unveiling of these direct quantum manifestations requires extremely sophisticated techniques, which we are unable to discuss here.

In one kind of experiment, an ion is confined to a region around equilibrium, the oscillations being reduced to zero-point fluctuations. Laser beams are used to manipulate the ion, to cool down its motion and to "see" it. The internal evolution can also be monitored, since the ion scatters laser light resonant with the distance between two levels. The light becomes invisible, however, if the ion "jumps" into a non-resonant third level. The scattered light suddenly reappears if the ion returns to one of the two levels resonating with the laser light. Figure 12.4 represents laser-induced fluorescence of a barium ion on the $\varphi_{6p} \rightarrow \varphi_{6s}$ transition versus time. Additional lamp irradiation interrupts the fluorescence by transitions from φ_{6s} to a metastable level.

Schrödinger believed in a statistical framework for quantum mechanics and thus, that sudden jumps of a single ion could not be observed: "We never experiment with just one electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this invariably entails ridiculous consequences..." (quoted in [37]).

If many ions are present, the trap confining potential competes with the Coulomb repulsion and a quasi-crystalline order is observed.

In another type of experiment, the roles of matter and radiation are exchanged. Photons with wavelengths in the millimeter range are made to bounce between

[5]This type of entanglement constitutes the basis for understanding the emergence of classical macrosystems from the quantum substrate (Sect. 14.2†).

the walls of a cavity with highly reflecting superconducting walls. Rydberg atoms (Sect. 6.1.2) [interacting strongly with microwaves and having a long meanlife (Problem 14 in Chap. 9)], are sent one by one to interact with the photons.

Consider two consecutive states in the Rydberg atom, φ_e and φ_g. The radiation field is described by the eigenstates of the harmonic oscillator χ_n in the occupation number representation (Sects. 3.3.1 and 9.8.2†), with the resonant photon frequency ω_{ph}. The atom-field coupling Hamiltonian may be approximated by

$$\hat{H}_{\text{coup}} = -\mathrm{i}\hbar \frac{\Omega_0}{2}(a\sigma_+ - a^+\sigma_-) , \tag{12.9}$$

where Ω_0 is proportional to the dipole moment of the Rydberg atom and to the mean square value of the electric field. The Jaynes–Cummings model applies (Sect. 3.4 and Problem 13 of Chap. 3). The resultant eigenenergies and eigenstates are

$$E_{n\pm} = \hbar\omega_{\text{ph}}\left(n + \frac{1}{2}\right) \pm \frac{\hbar\Omega_n}{2} ; \qquad \Omega_n = \Omega_0\sqrt{\frac{n+1}{2}}$$

$$\Psi_{n\pm} = \frac{1}{\sqrt{2}}\left(\varphi_e\chi_n \pm \mathrm{i}\varphi_g\chi_{n+1}\right) . \tag{12.10}$$

Inversion of (12.10) yields

$$\varphi_e\chi_n = \frac{1}{\sqrt{2}}\left(\Psi_{n+} + \Psi_{n-}\right) . \tag{12.11}$$

Up to an overall phase, the time-evolution of this state is given by

$$\begin{aligned}[\varphi_e\chi_n](t) &= \frac{1}{\sqrt{2}}\left[\exp\left(-\mathrm{i}\frac{\Omega_n t}{2}\right)\Psi_{n+} + \exp\left(\mathrm{i}\frac{\Omega_n t}{2}\right)\Psi_{n-}\right] \\ &= \cos\frac{\Omega_n t}{2}\varphi_e\chi_n + \sin\frac{\Omega_n t}{2}\varphi_g\chi_{n+1} .\end{aligned} \tag{12.12}$$

If the atom is in an initial state φ_e in free space, it decays to the final state φ_g, while simultaneously emitting a photon that escapes (Sect. 9.8.4†). In the present case, the photon gets trapped by the cavity, and the atom-field coupling results in a reversible energy exchange.

Assume now that the atom, initially in the state φ_e, interchanges energy with a field that does not have a definite number of photons ($\chi = \sum_n c_n\chi_n$). Applying (12.12), one obtains

$$[\varphi_e\chi](t) = \sum_n c_n\left(\cos\frac{\Omega_n t}{2}\varphi_e\chi_n + \sin\frac{\Omega_n t}{2}\varphi_g\chi_{n+1}\right) . \tag{12.13}$$

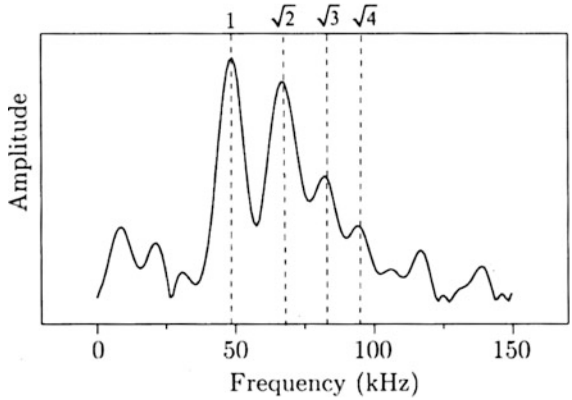

Fig. 12.5 Fourier transform of the time-dependent atomic signal detected after the interaction of a single Rydberg atom with a small field stored in a superconducting cavity. The average number of photons is $\bar{n} = 0.85 \pm 0.04$. The discrete peaks appear at frequencies which are proportional to the square root of the successive number of photons. (Reprinted with permission from Brune et al. [86], with authorization from the American Physical Society)

The probability of finding the atom in the state φ_e is

$$P_e(t) = \sum_n |c_n|^2 \frac{1 + \cos \Omega_n t}{2}. \tag{12.14}$$

Thus, the Fourier transform of the signal due to detection of the atoms leaving the cavity, displays peaks associated with transitions between states with a discrete number of photons (Fig. 12.5). The frequencies of the peaks are proportional to $\sqrt{n+1}$, as expected.

These cavity quantum electrodynamics (CQED) experiments show clear evidence of field "graininess," the fundamental hypothesis of Einstein in 1905 (Sect. 15.3.1). CQED experiments can also be considered to be modern versions of the photon box imagined by Einstein for the 1930 Solvay meeting (Fig. 15.3). Instead of weighing the box, information about the fields is imprinted on the exit ions, and photons are thus counted without being destroyed.

The cavity photons can also be prepared into a sort of Schrödinger cat state.

A thorough presentation of both ion and photon traps, covering both results and the experimental difficulties that have been overcome, can be found in [37].

12.3.4 A Quantum, Man-Made Mechanical Object

During 2010, quantum effects in the motion of a human-made object were experimentally observed for the first time [88]. A mechanical resonator – an oscillator –

displayed an isolated frequency such that $\hbar\omega = 2.6 \times 10^{-5}$ eV. It was cooled at 0.1 K using conventional cryogenic refrigeration, and thus $\hbar\omega/k_B T \approx 3$. Quantum measurements of the resonator were made using a superconducting qubit as a measurement device. The coupled system can be described by the Jaynes–Cummings model (Sect. 3.4). The system has proved to be much more stable than the resonator plus a classical measuring device. The following features appeared experimentally:

- The mechanical resonator was cooled to its ground state. The estimated number of phonons was $\langle 0|n|0\rangle = 0.07$.
- An individual quantum excitation (phonon) could be created in the resonator and the exchange of this excitation between the resonator and the entangled qubit was observed.
- A superposition state was generated in the resonator, with a qubit response in good agreement with theory.

Therefore, quantum mechanics applies as well to a mechanical object large enough to be seen with the naked eye.

However, one may not conclude that present experimental successes have *proved* the validity of quantum mechanics. It is worthwhile to remember that experiments can only prove that a theory is not correct, if their results contradict predictions of the theory. In the future, we expect more and even more subtle tests on the validity of quantum mechanics.