Appendix
The Conditional Nature of Single Particle Entanglement

In this appendix, we show how the uncertainty principle limits the ability of a single particle to entangle two distant systems. Entanglement is shown to occur with less than 1/2 probability of success, and this only after post-selection. We also apply our analysis to a specific example generally considered capable of entangling two atoms using one photon.

A.1 General Scenario

In the general situation one particle is used to entangle two distant systems Fig. A.1a, the state of the particle p is appropriately delocalized onto two paths A and B, i.e.,

$$|p\rangle = (1/\sqrt{2})\,(|1_A, 0_B\rangle + |0_A, 1_B\rangle)\,. \tag{A.1}$$

Although this state is formally entangled, it can readily be cast into a disentangled form, for example recombining the two particle paths and forming a balanced interferometer. It is congruently not capable of supporting itself two separate space-like measurements, as required for establishing nonlocality. Assume that these two paths host two separate systems, say A and B, two two-level systems (with ground state g and excited stated e) initially in their ground state $|g_A, g_B\rangle$, and that particle p is able to excite each of them separately. It would hence appear that after the interaction the initial disentangled state

$$|\psi_D\rangle = (1/\sqrt{2})(|1_A, 0_B\rangle + |0_A, 1_B\rangle)|g_A, g_B\rangle \tag{A.2}$$

becomes the entangled state

$$|\psi_E\rangle = (1/\sqrt{2})|0_A, 0_B\rangle(|g_A, e_B\rangle + |e_A, g_B\rangle). \tag{A.3}$$

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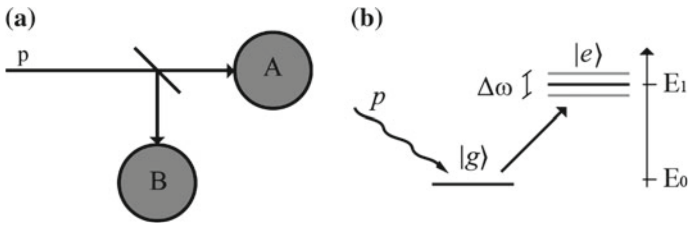


Fig. A.1 **a** General set-up: a single particle p is split onto two paths and made to interact with two distant systems A and B. **b** Energy level scheme for each particle-system interaction

This conclusion is, however, not precise. In fact, the property of A and B to be entangled is meaningful for a time interval $\Delta t \ll 1/\Delta\omega$, where $\Delta\omega$ is the linewidth of the excited level in each system Fig. A.1b. For longer time intervals, the excited states will begin to decay. On the other hand, in order for p to excite A or B, its energy uncertainty $\Delta\omega_p$ must be such that $\Delta\omega_p < \Delta\omega$. This implies that the time uncertainty in the arrival (or more generally, interaction) of particle p is $\Delta t_p > 1/\Delta\omega$. Hence, any given experiment able to test and eventually detect an entanglement between A and B requires a resolution in time less than the time uncertainty of particle p, so that the actual state is wholly uncertain between the particle p not being absorbed by system A or B or being absorbed, i.e., $|\psi\rangle = (1/\sqrt{2})(|\psi_D\rangle + |\psi_E\rangle)$, the first corresponding to the disentangled state of A and B both in the fundamental state, the second to the entangled condition. Thus, at its best, there is a maximum 1/2 probability of finding the two systems entangled.

A.1.1 Specific Example

As an example, we consider the interesting case in which p is a single photon and A and B are two two-level atoms, as described in Ref. [7]. Each atom, of transition frequency ω_a, is within a cavity able to contain photons of angular frequency ω_c such that $|\omega_a - \omega_c| \ll \omega_a + \omega_c$. The usual Jaynes–Cummings Hamiltonian [5] describing each single system atom-plus-photon reads

$$\hat{H} = \hbar\omega_c \hat{a}^+ \hat{a} + \hbar\omega_a \frac{\hat{\sigma}_z}{2} + \frac{\hbar\Omega}{2}(\hat{a}\hat{\sigma}^+ + \hat{a}^+\hat{\sigma}^-), \tag{A.4}$$

where $\hat{a}^+$ and $\hat{a}$ are the photon creation and annihilation operators and $\hbar\Omega$ denotes the amplitude of the atom-photon interaction. The characteristic angular frequency Ω can be evaluated through the relation [5]

$$\Omega^2 = \frac{4d^2\omega_a}{\hbar V \epsilon_0}, \tag{A.5}$$

where V is the cavity volume and d labels the transition dipole moment, i.e.,

$$d^2 = e^2 |\langle \psi_1 | \vec{r} | \psi_0 \rangle|^2, \tag{A.6}$$

$|\psi_0\rangle, |\psi_1\rangle$ being the fundamental and excited atomic states. For future use, we evaluate Eq. (A.5) for hydrogen atoms, for which

$$|\psi_0\rangle = |\psi_{n=1,l=0,m=0}\rangle = \frac{e^{-\frac{r}{a_0}}}{\sqrt{\pi a_0^3}}, \tag{A.7}$$

$$|\psi_1\rangle = |\psi_{n=2,l=1,m=0}\rangle = \frac{\frac{r}{a_0} e^{-\frac{r}{2a_0}}}{4\sqrt{2\pi a_0^3}}, \tag{A.8}$$

where $a_0 \simeq 0.52$ Å is Bohr radius. The angular frequency $\omega_a = \frac{E_1 - E_0}{\hbar}$ (E_0, E_1 are the energies of $|\psi_0\rangle, |\psi_1\rangle$) is determined through the relation $E_1 - E_0 \simeq 10.2eV$ and Eq. (A.6) is easily evaluated with the help of Eqs. (A.7), (A.8), thus obtaining

$$d^2 = \frac{2^{15}}{3^{10}} (e a_0)^2. \tag{A.9}$$

The above results and Eq. (A.5) give

$$\Omega(s^{-1}) \simeq \frac{50}{V^{\frac{1}{2}}} (V \rightarrow m^3). \tag{A.10}$$

Returning to the general case, the atom is conveniently described through the spin 1/2 formalism where the standard ladder operators $\hat{\sigma}^+ = |e\rangle\langle g|$ and $\hat{\sigma}^- = |g\rangle\langle e|$ are defined in terms of the ground and excited atomic states $|g\rangle$ and $|e\rangle$. The Hamiltonian $\hat{H}$ can be rewritten in the form

$$\hat{H} = \hat{H}_I + \hat{H}_{II}, \tag{A.11}$$

where

$$\hat{H}_I = \hbar\omega_c (\hat{a}^+ \hat{a} + \frac{\hat{\sigma}_z}{2}), \tag{A.12}$$

$$\hat{H}_{II} = \hbar \frac{\delta \hat{\sigma}_z}{2} + \hbar \frac{\Omega}{2} (\hat{a}\hat{\sigma}^+ + \hat{a}^+ \hat{\sigma}^-), \tag{A.13}$$

with $\delta = \omega_a - \omega_c$, are easily seen to commute. In turn, the eigenstates of $\hat{H}_I$ with a given number n of radiation quanta are given by $|n\rangle|g\rangle$, $|n\rangle|e\rangle$ and the states $|\psi_{1n}\rangle \equiv |n\rangle|e\rangle$, $|\psi_{2n}\rangle \equiv |n+1\rangle|g\rangle$ are degenerate with respect to $\hat{H}_I$. The matrix elements of the total Hamiltonian $\hat{H}$ in the subspaces $\{|\psi_{1n}\rangle, |\psi_{2n}\rangle\}$ read

$$H^{(n)} = \hbar \begin{pmatrix} n\omega_c + \frac{\omega_a}{2} & \frac{\Omega}{2}\sqrt{n+1} \\ \frac{\Omega}{2}\sqrt{n+1} & (n+1)\omega_c - \frac{\omega_a}{2} \end{pmatrix}. \tag{A.14}$$

Hereafter, we are interested in the case in which no more than one photon is present, i.e., we consider only $H^{(0)}$ whose eigenvalues turn out to be

$$E_\pm = \frac{\hbar\omega_c}{2} \pm \frac{\hbar\Omega_0(\delta)}{2}, \tag{A.15}$$

$(\Omega_0(\delta) = \sqrt{\delta^2 + \Omega^2})$. The corresponding eigenstates are

$$|+\rangle = \cos(\alpha/2)|\psi_{1n}\rangle + \sin(\alpha/2)|\psi_{2n}\rangle, \tag{A.16}$$

$$|-\rangle = -\sin(\alpha/2)|\psi_{1n}\rangle + \cos(\alpha/2)|\psi_{2n}\rangle, \tag{A.17}$$

with $\alpha = \arctan(\Omega/\delta)$. We now consider the situation in which, at time $t = 0$, the atom is in the ground state in the presence of one photon. Therefore, since $|+\rangle$, $|-\rangle$ are stationary states with respective energies E_+ and E_-, we have

$$\begin{aligned} &|\psi(t)\rangle = \\ &\cos(\alpha/2)\,[\cos(\alpha/2)|1\rangle|g\rangle - \sin(\alpha/2)|0\rangle|e\rangle]\, e^{-iE_- t/\hbar} \\ &+ \sin(\alpha/2)\,[\cos(\alpha/2)|0\rangle|e\rangle + \sin(\alpha/2)|1\rangle|g\rangle]\, e^{-iE_+ t/\hbar}, \end{aligned} \tag{A.18}$$

where $|\psi(t)\rangle$ is the state of the system atom-plus-photon satisfying the required initial conditions.

We now consider a photon with angular frequency ω_c sent on a beam splitter, after which it can reach at time $t = 0$ either a cavity A or a cavity B, tuned to ω_c. In both cavities there is an atom with transition frequency ω_a. Initially, both atoms A and B are in the ground state, and the two cavities are far enough that no direct atomic interaction takes place. Thus, the initial state $|\psi_T(0)\rangle$ of the total system atom A + atom B + photon reads

$$|\psi_T(0)\rangle = \left(\frac{|1_A, 0_B\rangle + |0_A, 1_B\rangle}{\sqrt{2}}\right)|g_A, g_B\rangle, \tag{A.19}$$

with self-explanatory symbols. As a consequence, we readily obtain, with the help of Eq. (A.19),

$$\begin{aligned} &|\psi_T(t)\rangle = \\ &= [\frac{1}{\sqrt{2}}\cos^2(\alpha/2)|1_A, 0_B\rangle|g_A, g_B\rangle - \frac{1}{\sqrt{2}}\cos(\alpha/2)\sin(\alpha/2)|0_A, 0_B\rangle|e_A, g_B\rangle]e^{-iE_- t/\hbar} \\ &+ [\frac{1}{\sqrt{2}}\sin(\alpha/2)\cos(\alpha/2)|0_A, 0_B\rangle|e_A, g_B\rangle + \frac{1}{\sqrt{2}}\sin^2(\alpha/2)|1_A, 0_B\rangle|g_A, g_B\rangle]e^{-iE_+ t/\hbar} \\ &+ [\frac{1}{\sqrt{2}}\cos^2(\alpha/2)|1_B, 0_A\rangle|g_B, g_A\rangle - \frac{1}{\sqrt{2}}\cos(\alpha/2)\sin(\alpha/2)|0_B, 0_A\rangle|e_B, g_A\rangle]e^{-iE_- t/\hbar} \end{aligned}$$

$$
\begin{aligned}
&+ [\frac{1}{\sqrt{2}} \sin(\alpha/2)\cos(\alpha/2)|0_B, 0_A\rangle|e_B, g_A\rangle + \frac{1}{\sqrt{2}}\sin^2(\alpha/2)|1_B, 0_A\rangle|g_B, g_A\rangle]e^{-iE_+t/\hbar} \\
&\qquad = [\cos^2(\alpha/2)e^{-iE_-t/\hbar} + \sin^2(\alpha/2)e^{-iE_+t/\hbar}]\left(\frac{|1_A, 0_B\rangle + |0_A, 1_B\rangle}{\sqrt{2}}\right)|g_A, g_B\rangle \\
&\qquad + \sin(\alpha/2)\cos(\alpha/2)\left(e^{-iE_+t/\hbar} - e^{-iE_-t/\hbar}\right)|0_A, 0_B\rangle\left(\frac{|e_A, g_B\rangle + |g_A, g_B\rangle}{\sqrt{2}}\right) \\
&\qquad \equiv |\psi_D(t)\rangle + |\psi_E(t)\rangle,
\end{aligned}
\tag{A.20}
$$

where $|\psi_D(t)\rangle$ (both atoms in the ground state $\rightarrow |g_A, g_B\rangle$) forbids entanglement between the atoms A and B, while $|\psi_E(t)\rangle$ (photon disappeared $\rightarrow |0_A, 0_B\rangle$) admits entanglement. On the other hand we have, with the help of Eq. (A.15),

$$
\langle\psi_D(t)|\psi_D(t)\rangle = \cos^4\left(\frac{\alpha}{2}\right) + \sin^4\left(\frac{\alpha}{2}\right) + 2\sin^2\left(\frac{\alpha}{2}\right)\cos^2\left(\frac{\alpha}{2}\right)\cos(\Omega_0 t), \tag{A.21}
$$

$$
\langle\psi_E(t)|\psi_E(t)\rangle = 2\cos^2\left(\frac{\alpha}{2}\right)\sin^2\left(\frac{\alpha}{2}\right)[1 - \cos(\Omega_0 t)]. \tag{A.22}
$$

Thus, total entanglement requires $\alpha = \arctan(\Omega/\delta) \simeq \pi/2$, for which

$$
\langle\psi_D(t)|\psi_D(t)\rangle = \frac{1}{2}[1 + \cos(\Omega t)], \tag{A.23}
$$

$$
\langle\psi_E(t)|\psi_E(t)\rangle = \frac{1}{2}[1 - \cos(\Omega t)]. \tag{A.24}
$$

The condition $\langle\psi_E(t)|\psi_E(t)\rangle = 1$ and $\langle\psi_D(t)|\psi_D(t)\rangle = 0$ emerges for times t_n given by

$$
t_n = \frac{(2n+1)\pi}{\Omega_0}. \tag{A.25}
$$

Moreover, the condition $\alpha \simeq \pi/2$ implies that $\delta/\Omega_0 \ll 1$. However, δ cannot be less than the intrinsic uncertainty $\Delta\omega$ of the photon frequency, so that the photon must have an uncertainty in time $\Delta t > 2\pi/\Delta\omega \geq 2\pi/\delta$. On the other hand, to use Eq. (A.22) we need a resolution in time Δt such that $\Delta t < 2\pi/\Omega_0$, so that, since $\Omega_0 = (\delta^2 + \Omega^2)^{1/2}$, $\Delta t \ll 2\pi/\delta$, which does not agree with the minimum uncertainty Δt, i.e., $\Delta t \geq 2\pi/\delta$. Specifically, the condition on the required time resolution contradicts the uncertainty in the arrival times of the photon on the two atoms. On the physically available time resolution Δt experiments yield the time averages, i.e., in Eqs. (A.23) and (A.24), the time t possesses an indetermination Δt. Since this limit is a consequence of the uncertainty principle, it implies that our formulation of Eq. (A.20) as parametrized in time when $\alpha \simeq \pi/2$ is incorrect, and the true wavefunction that describes our system must not contain t, i.e., be

$$
|\psi_T\rangle = \frac{1}{\sqrt{2}}[|\psi_D\rangle + |\psi_E\rangle], \tag{A.26}
$$

where

$$|\psi_D\rangle = \frac{1}{\sqrt{2}}\left[|1_A, 0_B\rangle + |0_A, 1_B\rangle\right]|g_A, g_B\rangle, \tag{A.27}$$

$$|\psi_E\rangle = \frac{1}{\sqrt{2}}|0_A, 0_B\rangle\left[|e_A, g_B\rangle + |g_A, e_B\rangle\right]. \tag{A.28}$$

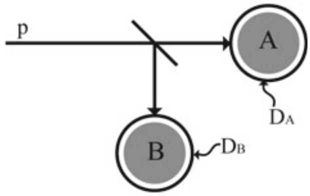
Formally, our attempt to entangle one particle using two distant systems is achieved through an appropriate interaction such that the prepared input state $|1\rangle_p|\alpha\rangle_A|\beta\rangle_B$ evolves to the final state $|0\rangle_p|\gamma\rangle_{AB}$, with the constraint that $|\gamma\rangle_{AB}$ is entangled. The limits associated to the use of one particle to entangle two distant systems can, in this vein, also be analyzed considering the details of the interaction Hamiltonian that represents the evolution $|0\rangle_p|\gamma\rangle_{AB} = \hat{a}\hat{P}|1\rangle_p|\alpha\rangle_A|\beta\rangle_B$, where $\hat{a}$ is the annihilation operator for p, and $\hat{P}$ is the operator that describes the evolution for the systems. Assume now that no interaction term involves the entangling particle and the two systems together. This means that, using for example the standard spinorial notation for two two-level systems A and B, $\hat{P} = \hat{P}(\hat{\sigma}_{z,A}, \hat{\sigma}_{z,B})$ is a linear combination of $\hat{\sigma}_{z,A}, \hat{\sigma}_{z,B}$. Now, the maximally entangled Bell-basis are the eigenstates of nonlinear operators in the spin of the two systems, such as $\hat{\sigma}_z^2 = (\hat{\sigma}_{z,A} + \hat{\sigma}_{z,B})^2$ and $\hat{\sigma}_x^2 = (\hat{\sigma}_{x,A} + \hat{\sigma}_{x,B})^2$, and the latter does not commute with $\hat{\sigma}_{z,A}, \hat{\sigma}_{z,B}$, and hence with $\hat{P}$ [2]. Specific combinations of $\hat{\sigma}_{x,A}$ and $\hat{\sigma}_{x,B}$ can share eigenstates with the disentangled basis, and a maximum overlap of half the Hilbert space occurs when the interaction involves the total spin operators of A and B. This is the case of the previously discussed Jaynes–Cummings interaction, where the Hamiltonian has terms with $\hat{\sigma}_i = \hat{\sigma}_{i,A} + \hat{\sigma}_{i,B}$, $(i = x, y, z)$. The requirement that the particle system interaction involves nonlinear operators, such as $\hat{\sigma}^-\hat{\sigma}^+ + \hat{\sigma}^+\hat{\sigma}^-$, where $\hat{\sigma}^\pm = \hat{\sigma}_A^\pm + \hat{\sigma}_B^\pm$, and $\hat{\sigma}_{A/B}^\pm = \hat{\sigma}_{x,A/B} \pm i\hat{\sigma}_{y,A/B}$, implies that a three-particle interaction term must be involved, that is, that the two systems must locally interact and separate subsequently (i.e., they cannot be prepared as "distant"), as is well known to occur for standard entanglement sources.

A.1.2 Remarks on the Conditional Nature

These results indicate that one can achieve conditional maximum 50% entanglement between two distant systems using a single particle.[1] Conditional means that of all the results on $(\hat{\sigma}_{i,A}, \hat{\sigma}_{i,B})$ non-local correlations can only be detected in post-selected ensembles. This may be misinterpreted as being a practical limitation, and hence that total entanglement can actually be distilled from this conditional ensemble before measurements are carried out. In order to sift an entangled state from $|\psi_T\rangle$, we can enclose the outer surface of each of the two cavities A and B with two ideal photon detectors D_A, D_B (Fig. A.2), and simultaneously open A and B at a given instant of

[1]The same factor of 50% has been obtained in the field of linear teleportation [1, 4, 6].

Fig. A.2 Entangling system



time ($t = 0$). If either D_A or D_B clicks (at $t = 0$), $|\psi_T\rangle$ is projected (at $t = 0$) onto $|\psi_D\rangle$, whose atomic component

$$|\phi_D(t=0)\rangle = |g_A, g_B\rangle \tag{A.29}$$

is disentangled, while, if neither D_A nor D_B clicks, the mixed state is projected onto the state $|\psi_E\rangle$, whose atomic component

$$|\phi_E(t=0)\rangle = \frac{1}{\sqrt{2}}\left[|e_A, g_B\rangle + |g_A, e_B\rangle\right] \tag{A.30}$$

is entangled. We note that this result is obviously valid whenever the typical time T_C necessary to cross the cavity is much smaller than the oscillation time $2\pi/\Omega$. This is the case for the example referring to hydrogen atoms in a cavity of about $V = 10^{-9} m^3$, for which, with the help of Eq. (A.10), $2\pi/\Omega = 4 \cdot 10^{-6} s$, while $T_C \simeq \frac{V^{1/3}}{c} \simeq \frac{10^{-11}}{3} s$. In fact, the validity of Eq. (A.30) hides a more subtle but profound assumption. We have an entangled pair of systems only once we have certainty that both detectors D_A and D_B have not fired. This shared knowledge at A and B can be readily achieved assuming that the time it takes a classical signal to reach from A to B would be smaller than the characteristic time $2\pi/\Omega$ in which the system oscillates. This apparently trivial condition means that for any given systems A and B, there is a distance beyond which the entangling scheme breaks down. The existence of this distance means that the two systems A and B obey Einstein locality [3].

A.1.3 Remarks on Reversibility

The entire matter as to if and how a specific process can or cannot lead to entanglement can be analyzed in terms of microscopic reversibility. Specifically, consider a process in which an isolated system with N independent input particles leads to N output particles at space-like distances. Should the final wavefunction be entangled, the outcomes of the N independent experiments that can be carried out on the N output particles would be correlated, so that the phase-space of the outcoming state would be smaller than that of the incoming state, thus violating microscopic reversibility. Congruently, the Jaynes–Cummings model associated with the split photon interacting with the two single atoms described by Eq. (A.4) contains terms like $\hat{a}\hat{\sigma}^{+}_{A/B}$, so that the number of particles is constant. Thus, entanglement can only occur if the number of particles from input to output changes. More precisely, if each particle has the same number of internal states both at input and output, the number of output particles susceptible to space-like experiments must increase, as this is the only way to preserve the phase-space of the system and introduce correlations.

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