1)

The Aspect Experiment. (Paper 54 Notes 7)

(http://roxanne.roxanne.org/epr/experiment.html)

This is a good site for the description of the Aspect experiment and the EPR paradox. Two photons are emitted at the same time and circularly polarized in the opposite directions. The photons travel along different paths and filters define their orientations $\underline{a}$ and $\underline{b}$, with an angle θ subtended between the two directions. A circularly polarized photon:

$$\underline{A}^{(1)} = \frac{A^{(0)}}{\sqrt{2}} (\underline{i} - i\underline{j}) e^{i\phi} \quad -(1)$$

is split into:

$$\underline{A}^{(1)}_a = \frac{A^{(0)}}{\sqrt{2}} \underline{i} e^{i\phi} \quad -(2)$$

and:

$$\underline{A}^{(1)}_b = -i\frac{A^{(0)}}{\sqrt{2}} \underline{j} e^{i\phi} \quad -(3)$$

The polarization filter PA_1 is set at $\underline{a}$, and PA_2 is set at $\underline{b}$. So PA_1 lets through $\underline{A}^{(1)}_a$ and PA_2 lets through $\underline{A}^{(1)}_b$. A photo-multiplier tube detects either $\underline{A}^{(1)}_a$ or $\underline{A}^{(1)}_b$, one detector for $\underline{A}^{(1)}_a$ and one detector for $\underline{A}^{(1)}_b$. A $+1$ is registered for $\underline{A}^{(1)}_a$ and a -1 for $\underline{A}^{(1)}_b$. The ± 1 signals are collected on a coincidence

2) counter.

This procedure occurs for two complete photons, one is right circularly polarized:

$$\underline{A}^{(1)}_{R} = \frac{A^{(0)}}{\sqrt{2}} \left(\underline{i} - i\underline{j} \right) e^{i\phi} \quad - (1a)$$

and the other is left circularly polarized:

$$\underline{A}^{(1)}_{L} = \frac{A^{(0)}}{\sqrt{2}} \left(\underline{i} + i\underline{j} \right) e^{i\phi} \quad - (4)$$

so there are $\underline{A}^{(1)}_{Ra}$, $\underline{A}^{(1)}_{Rb}$, $\underline{A}^{(1)}_{La}$ and $\underline{A}^{(1)}_{Lb}$.
The states $\underline{A}^{(1)}_{Ra}$ and $\underline{A}^{(1)}_{La}$ both register a $+1$ and $\underline{A}^{(1)}_{Rb}$ and $\underline{A}^{(1)}_{Lb}$ both register a -1.

The coincidence counter only accepts results if the time delay between receiving signals from the PMT tubes on sides A and B is less than a certain time t. The latter is half the time it takes for a signal at c to travel from one filter to the other. If an event occurs within t the result on side A ($+1$ or -1) is multiplied by the result from side B and the average value found from repeated measurements. The average value is defined by the expectation

3) value. The latter is the sum of all the resulting values multiplied by the probability for that value:

$$E = P_{++} - P_{+-} - P_{-+} + P_{--} \quad -(5)$$

This is a function of the filter orientation, or the angle θ between $\underline{a}$ and $\underline{b}$.

Here P_{++} is the probability that both detectors registered a + and P_{--} is the probability that both detectors registered a minus. The probabilities are measured experimentally by recording the number of counts of a particular type and dividing this record by the total number of counts recorded. Thus for example, P_{-+} is the number of times the left detector registered -1 at the same time as the right detector measured $+1$. The "same time" means "within the T limit".

Relation to ECE Theory

Within the factor $A^{(0)}$, $\underline{A}^{(1)}_{Ra}$, $\underline{A}^{(1)}_{Rb}$, $\underline{A}^{(1)}_{La}$ and $\underline{A}^{(1)}_{Lb}$ are tetrads, or wave-functions. So the Aspect experiment investigates

4) The statistical nature of tetrads. By "statistical" in this context is meant statistical averaging of causal wave functions. In ECE theory (generally covariant wave mechanics) the Aspect experiment is considered as follows. Filter PA_1 detects linear polarization along a direction given by $\underline{a}$. Filter PA_2 detects $\underline{b}$. The expectation value is:

$$\boxed{E_{(\underline{a}, \underline{b})} = \cos 2\theta}, \quad -(6)$$

and this is what is measured experimentally by the Aspect experiment. So we need to explain eqn. (6) using ECE theory in the non-relativistic quantum limit - the limit of the Schrödinger equation. The latter is (see notes 5 and 6):

$$q_\mu^a(t_1, \underline{r}_1) = e^{iS/\hbar} q_\mu^a(t_2, \underline{r}_2). \quad -(7)$$

Thus:

$$\underline{A}^{(1)}(t_1, \underline{r}_1) = e^{iS/\hbar} \underline{A}^{(1)}(t_2, \underline{r}_2). \quad -(8)$$

Now make the identification:

5)

$$\theta := s / \hbar, \quad - (9)$$

and note that the following is always true:

$$e^{i\theta} = e^{2i\theta} e^{-i\theta} \quad - (10)$$

where

$$e^{2i\theta} = \cos 2\theta + i \sin 2\theta. \quad - (11)$$

Therefore:

$$\cos 2\theta = \mathrm{Re} \left(e^{i\theta} e^{i\theta} \right) \rightarrow (12)$$

$$\boxed{\cos 2\theta = \mathrm{Re} \left(e^{i\theta} e^{2i\theta} e^{-i\theta} \right)} \quad - (13)$$

If we denote:

$$\phi = e^{i\theta}, \quad \phi^* = e^{-i\theta} \quad - (14)$$

and

$$\Omega = e^{2i\theta} \quad - (15)$$

Then:

$$\boxed{\cos 2\theta = \phi \, \Omega \, \phi^*} \quad - (16)$$

From eqs. (8) and (9) it follows that:

$$\underline{A}^{(1)} = e^{2i\theta} \underline{A}^{(2)} \quad - (17)$$

where

$$A^{(2)} = A^{(1)*} \quad (18)$$

6) and:

$$\theta = \phi = S/\hbar \quad -(19)$$

is the electromagnetic phase.

Equation (16) is very similar to the definition of expectation value in quantum mechanics:

$$\langle \Omega \rangle = \int \psi^* \Omega \psi \, d\tau \Big/ \int \psi^* \psi \, d\tau, \quad -(20)$$

where τ is volume. Usually the denominator is normalized to unity, so:

$$\langle \Omega \rangle = \int \psi^* \Omega \psi \, d\tau. \quad -(21)$$

The meaning of this is explained by Atkins on pp. 85 ff.: the expectation value is a weighted sum of the eigenvalues of Ω. The wave function is expanded as:

$$\psi = \sum_n c_n \psi_n \quad -(22)$$

where

$$\Omega \psi_n = \omega_n \psi_n. \quad -(23)$$

From Atkins p. 25 ff the amplitude of a light wave at point x is $a \exp(2\pi i x / \lambda)$ where λ is its wavelength. Its amplitude at a fixed point P_1 is $a \exp(2\pi i x_1 / \lambda)$

7) and at a fixed point P_2 is $a\exp(2\pi i x_2/\lambda)$

So:

$$\phi(P_2) = a e^{2\pi i x_2/\lambda}$$

$$= a e^{2\pi i(x_2-x_1)/\lambda} e^{2\pi i x_1/\lambda}$$

$$= e^{2\pi i(x_2-x_1)/\lambda}\phi(P_1), \quad -(24)$$

i.e. $$\phi(P_2) = e^{i\phi_1}\phi(P_1), \quad -(25)$$

where $$\phi_1 = 2\pi(x_2-x_1)/\lambda \quad -(26)$$

is the phase length. As we saw in notes 4-6 the phase length is minimized by the Fermat Principle of Least Time. The action S is minimized by the Hamilton Principle of least action. This leads to the Schrodinger equation. In ECE theory this is a causal wave equation. Now identify:

$$\theta = \pi(x_2-x_1)/\lambda \quad -(27)$$

and:

$$\boxed{\phi(P_2) = e^{2i\theta}\phi(P_1)} \quad -(28)$$

This is always true for any electromagnetic

8)
wave. In the special case:

$$\psi(P_1) = \psi^*(P_2) \quad -(29)$$

we recover eqn. (17). In this case:

$$\cos 2\theta = \mathrm{Re}\left(\psi e^{2i\theta}\psi^*\right) \quad -(30)$$

$$= \mathrm{Re}\left(\psi\psi\right). \quad -(31)$$

Note that the Schrödinger equation is eqn. (28), in which $e^{2i\theta}$ is regarded as an operator. This is true both for a light wave as in the Aspect experiment, or a matter wave. So the quantity $\cos 2\theta$ where θ is now the angle between directions a and b is related from eq. (31) to the squared amplitude of the light wave. If $\theta = \pi/4$ then $\cos 2\theta = 0$, and if $\theta = 0$, $\cos 2\theta = 1$

In ECE theory these are tetrad amplitudes. So the Aspect experiment is understood entirely as a phenomenon of tetrad waves, i.e. waves of spacetime itself, non-locality being understood in terms of the spin connection.