20

The Franson Experiment

20.1 Introduction

Experimental violations of the Bell and Leggett–Garg inequalities studied in Chapters 17 and 19, respectively, show that quantum states of systems under observation (SUOs) cannot be interpreted classically. Interpretations that claim to do this require contextually incomplete modifications of classical principles, such as a breakdown of classical locality. Such modifications merely serve to make standard quantum mechanics (QM) more appealing.

However, that is only one side of the observer–SUO fence. In this chapter, we start to explore the other side of that fence, where the observer and their apparatus live. Our focus is a thought experiment proposed by Franson (Franson, 1989), which suggests that apparatus cannot always be treated classically. Three scenarios are discussed, each involving different time scales, with corresponding different outcomes.

20.2 The Franson Experiment

In the following, we refer to "photons" as if they were actual particles, but that is only a convenient and intuitive way of describing what at the end of the day are just clicks in detectors. There are experiments, for example, where it is not reasonable to think of the sources of photons (such as certain crystals) as point like (Paul, 2004).

Franson's proposed experiment FRANSON has parameters that can alter outcomes significantly. There are three significant choices of parameters, leading to three distinct scenarios labeled FRANSON-1, FRANSON-2, and FRANSON-3. The basic architecture consists of a coherent pair of photons, produced at a localized source S, sent in opposite directions toward a pair of separated Mach–Zehnder interferometers, as shown in Figure 20.1. Each photon passes through its own interferometer and, depending on path taken, can suffer a change in

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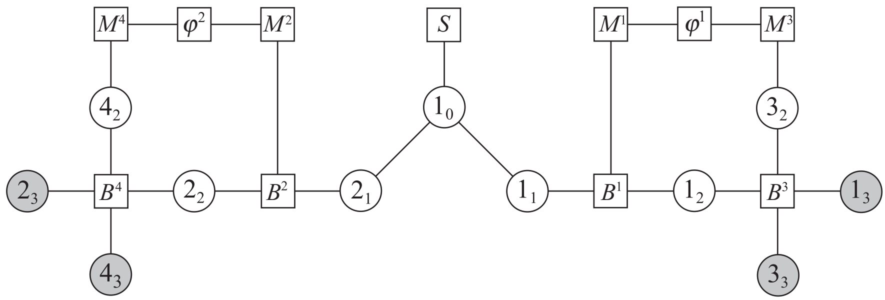

Figure 20.1. FRANSON-1: the Franson experiment for $\Delta T < \tau_2 \ll \tau_1$. S is the photon pair source, the B^i are beam splitters, the M^i are mirrors, and the ϕ^i are phase changers.

phase ϕ and a time delay ΔT. The time delay ΔT is assumed the same for each interferometer in any given run. The phase changes ϕ^1, ϕ^2 associated with the different interferometers can be altered by the observer, but are fixed before and during each run.

The experiment hinges on the relationship between three characteristic times (Franson, 1989).

Coherence Time τ_1

In quantum optics experiments, a finite electromagnetic wave train of length L moving at the speed of light c takes a time $\tau \equiv L/c$ to pass a given point. Such a time is known as a *coherence time*. In the Franson experiment, the coherence time τ_1 is that associated with the production of the photon pair by stage Σ_1. It is a characteristic of the photon pair source S and of the collimation procedures applied subsequently. While τ_1 cannot be altered, it can be determined empirically. We shall assume that τ_1 is the same for each photon.

Emission Time τ_2

The second characteristic time is τ_2, the effective time interval within which both photons in a pair can be said to have been emitted. This can be measured during calibration by coincidence observations of detectors 1_3 and 2_3 with all beam-splitters removed. It is assumed τ_2 can be determined empirically and that $\tau_2 \ll \tau_1$. This last inequality is crucial to FRANSON because when this inequality holds, the observer has no way of knowing when a photon pair was created during the relatively long time interval τ_1.[1] It is this lack of knowledge that leads to quantum interference in the FRANSON-3 scenario discussed below. The spectacular aspect of FRANSON is that unlike the double-slit experiment,

[1] Of course, “photon creation” is a vacuous metaphysical picture extrapolated from observations done *after* the source has been triggered. There is no evidence, based on the given apparatus, for the belief that anything has been “created” at S.

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where the observer does not know from which point in space a photon came, here the observer does not know at which point in time the photon pair was produced.

Travel Time Difference ΔT

The third characteristic time is ΔT, the time difference between a photon traveling along the short arm of its interferometer and along its long arm. This time is adjustable but fixed during each run and is assumed the same for each of the two interferometers in that run.

There are three scenarios we shall discuss: FRANSON-1, for which $\Delta T \ll \tau_2$; FRANSON-2, for which $\tau_1 \ll \Delta T$; and FRANSON-3, for which $\tau_2 \ll \Delta T \ll \tau_1$. In Franson's original analysis (Franson, 1989), photon spin did not play a role. Therefore, in all scenarios considered here, photon spin is assumed fixed once a given photon pair has been created.

20.3 FRANSON-1: $\Delta T \ll \tau_2$

The relevant figure for this scenario is Figure 20.1. We discuss the experiment in terms of its stages, as follows.

Stage Σ_0

The initial total state is

$$|\mathbf{\Psi}_0) \equiv |s_0\rangle \otimes \widehat{\mathbb{A}}_0^1 \mathbf{0}_0, \tag{20.1}$$

where $|s_0\rangle$ represents the initial source spin state.

Stage Σ_0 to Stage Σ_1

By stage Σ_1, the initial state has split into a correlated pair of photons moving in opposite directions. The creation of this pair by this stage is represented by the action of the contextual evolution operator $U_{1,0}$:

$$|\mathbf{\Psi}_1) \equiv U_{1,0}|\mathbf{\Psi}_0) = |s_1\rangle \otimes \widehat{\mathbb{A}}_1^1 \widehat{\mathbb{A}}_1^2 \mathbf{0}_1, \tag{20.2}$$

where $|s_1\rangle$ represents the combined spin state of the photon pair at this stage.

Stage Σ_1 to Stage Σ_2

The stage-Σ_1 photons pass through beam splitters B^1 and B^2 as shown. One output channel from each beam splitter leads directly to a final beam splitter, while the other output channel is deflected by a mirror through a phase changer before being deflected onto that final beam splitter. The four beam splitters B^i, $i = 1, 2, 3, 4$, are parametrized by real transmission and reflection coefficients t^i, r^i respectively, according to the prescription given by Eq. (11.28).

The labstate evolution is given by

$$
\begin{aligned}
U_{2,1}\left\{|s_1\rangle \otimes \widehat{\mathbb{A}}_1^1\widehat{\mathbb{A}}_1^2\mathbf{0}_1\right\} &= |s_2\rangle \otimes \left\{t^1\widehat{\mathbb{A}}_2^1 + ir^1e^{i\phi^1}\widehat{\mathbb{A}}_2^3\right\}\left\{t^2\widehat{\mathbb{A}}_2^2 + ir^2e^{i\phi^2}\widehat{\mathbb{A}}_2^4\right\}\mathbf{0}_2 \\
&= |s_2\rangle \otimes \left\{\begin{array}{l} t^1t^2\mathbf{3}_2 + ir^1t^2e^{i\phi^1}\mathbf{6}_2 + \\ ir^2t^1e^{i\phi^2}\mathbf{9}_2 - r^1r^2e^{i(\phi^1+\phi^2)}\underline{\mathbf{12}}_2 \end{array}\right\},
\end{aligned}
\tag{20.3}
$$

where ϕ^1 and ϕ^2 are total phase change factors due to the increased path length of the long arms of the interferometers and phase-shift plates introduced in those long arms by the observer. In the last line in (20.3), we show the computation basis representation (CBR) of the expression in the previous line.

Stage Σ_2 to Stage Σ_3

There are four terms to consider in the transition from Σ_2 to Σ_3:

$$
\begin{aligned}
U_{3,2}\left\{|s_2\rangle \otimes \widehat{\mathbb{A}}_2^1\widehat{\mathbb{A}}_2^2\mathbf{0}_2\right\} &= |s_3\rangle \otimes \left\{t^3\widehat{\mathbb{A}}_3^1 + ir^3\widehat{\mathbb{A}}_3^3\right\}\left\{t^4\widehat{\mathbb{A}}_3^2 + ir^4\widehat{\mathbb{A}}_3^4\right\}\mathbf{0}_3, \\
U_{3,2}\left\{|s_2\rangle \otimes \widehat{\mathbb{A}}_2^3\widehat{\mathbb{A}}_2^2\mathbf{0}_2\right\} &= |s_3\rangle \otimes \left\{t^3\widehat{\mathbb{A}}_3^3 + ir^3\widehat{\mathbb{A}}_3^1\right\}\left\{t^4\widehat{\mathbb{A}}_3^2 + ir^4\widehat{\mathbb{A}}_3^4\right\}\mathbf{0}_3, \\
U_{3,2}\left\{|s_2\rangle \otimes \widehat{\mathbb{A}}_2^1\widehat{\mathbb{A}}_2^4\mathbf{0}_2\right\} &= |s_3\rangle \otimes \left\{t^3\widehat{\mathbb{A}}_3^1 + ir^3\widehat{\mathbb{A}}_3^3\right\}\left\{t^4\widehat{\mathbb{A}}_3^4 + ir^4\widehat{\mathbb{A}}_3^2\right\}\mathbf{0}_3, \\
U_{3,2}\left\{|s_2\rangle \otimes \widehat{\mathbb{A}}_2^3\widehat{\mathbb{A}}_2^4\mathbf{0}_2\right\} &= |s_3\rangle \otimes \left\{t^3\widehat{\mathbb{A}}_3^3 + ir^3\widehat{\mathbb{A}}_3^1\right\}\left\{t^4\widehat{\mathbb{A}}_3^4 + ir^4\widehat{\mathbb{A}}_3^2\right\}\mathbf{0}_3.
\end{aligned}
\tag{20.4}
$$

This is all the information needed for our computer algebra program MAIN to evaluate the answers to all maximal questions. These answers turn out to be complicated, long polynomials in the t^i and r^i parameters, so are not listed here. However, setting them to the empirically useful value $t^i = r^i = 1/\sqrt{2}$, $i = 1, 2, 3, 4$, as assumed by Franson (Franson, 1989), gives the relative coincidence rates

$$
\begin{aligned}
\Pr\left(\widehat{\mathbb{A}}_3^1\widehat{\mathbb{A}}_3^2\mathbf{0}_3|\Psi_0\right) &= \sin^2\left(\tfrac{1}{2}\phi^1\right)\sin^2\left(\tfrac{1}{2}\phi^2\right), \\
\Pr\left(\widehat{\mathbb{A}}_3^3\widehat{\mathbb{A}}_3^2\mathbf{0}_3|\Psi_0\right) &= \cos^2\left(\tfrac{1}{2}\phi^1\right)\sin^2\left(\tfrac{1}{2}\phi^2\right), \\
\Pr\left(\widehat{\mathbb{A}}_3^1\widehat{\mathbb{A}}_3^4\mathbf{0}_3|\Psi_0\right) &= \sin^2\left(\tfrac{1}{2}\phi^1\right)\cos^2\left(\tfrac{1}{2}\phi^2\right), \\
\Pr\left(\widehat{\mathbb{A}}_3^3\widehat{\mathbb{A}}_3^4\mathbf{0}_3|\Psi_0\right) &= \cos^2\left(\tfrac{1}{2}\phi^1\right)\cos^2\left(\tfrac{1}{2}\phi^2\right).
\end{aligned}
\tag{20.5}
$$

Each of these rates shows angular dependence due to independent "photon self-interference" within each separate interferometer. This form of interference will be referred to as *local*. There are no *global* interference effects involving both interferometers and no post selection of data is required.

20.4 FRANSON-2: $\tau_1 \ll \Delta T$

In this variant of the Franson experiment, the photon wave trains 3_2, 4_2 reflected at B^1 and B^2, respectively, travel along the long arms of their respective interferometers at the speed of light or less, depending on the medium through which

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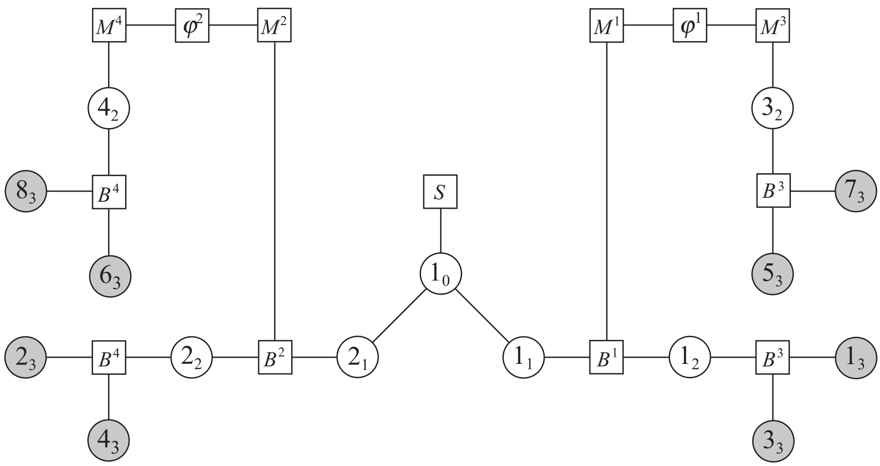

Figure 20.2. FRANSON-2: the Franson experiment for $\tau_2 \ll \tau_1 \ll \Delta T$.

they move. Because now the travel time difference ΔT is very much greater than the coherence time τ_1, these wave trains arrive at B^3 and B^4 long after the transmitted wave trains 1_2 and 2_2 have impinged on B^3 and B^4, respectively. In consequence, no local or global interference can take place. In fact, the observer can now obtain total information concerning the timing of each coincidence outcome in every run of the experiment and know precisely what path was taken by each photon.

Under this circumstance, the four original detectors $1_3, 2_3, 3_3$, and 4_3 used in FRANSON-1 now have to be regarded as *eight* separate detectors, i_3, $i = 1, 2, \ldots, 8$, as shown in Figure 20.2. The first four of these register photon clicks from short-path photons, while the last four signal clicks from those that have traveled the long paths. This information is specific to each photon and does not involve any photon pairs.

Significantly, the final-stage quantum register involved in this scenario and the next one, FRANSON-3, is 256-dimensional. However, our computer algebra program MAIN has no difficulty dealing with this because it has been encoded to process only the relevant contextual Hilbert spaces, and these are of greatly reduced dimensions.

This demonstrates a fundamental point about apparatus. In the conventional usage of apparatus, experimentalists tend to regard their equipment as having some sort of "transtemporal" identity, or persistence. In Figure 20.2, for example, beam splitters B^3 and B^4 would most likely persist in the laboratory as material objects, during the long interval ΔT between their interaction with wave-trains 1_2 and 2_2 and with the delayed wave-trains 3_2 and 4_2. Even classically, however, this need not be the case. It is conceivable that ΔT could be so long, such as several years, that the beam splitters could be destroyed and rebuilt at leisure between the observation of any short-arm photons and any long-arm photons.

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Whatever the actuality in the laboratory, from a quantum point of view, the beam splitters receiving short- and long-arm photons should be considered as completely separate pieces of equipment in this scenario (but not in the next). In other words, apparatus and how it is used is time dependent. The analysis in the next section shows that the rules for doing this can be quite nonclassical and appear to violate the ordinary rules of causality.

For the FRANSON-2 scenario, $\tau_1 \ll \Delta T$, the dynamics follows the same rules as in the previous section up to the transition from stage Σ_2 to stage Σ_3. At this point, the transformation rules have to take into account the possibility that the observer could know the timings of all events. The rules for this transition are now

$$\begin{aligned}
U_{3,2}\left\{|s_2\rangle \otimes \widehat{\mathbb{A}}_2^1\widehat{\mathbb{A}}_2^2\mathbf{0}_2\right\} &= |s_3\rangle \otimes \left\{t^3\widehat{\mathbb{A}}_3^1 + ir^3\widehat{\mathbb{A}}_3^3\right\}\left\{t^4\widehat{\mathbb{A}}_3^2 + ir^4\widehat{\mathbb{A}}_3^4\right\}\mathbf{0}_3,\\
U_{3,2}\left\{|s_2\rangle \otimes \widehat{\mathbb{A}}_2^3\widehat{\mathbb{A}}_2^2\mathbf{0}_2\right\} &= |s_3\rangle \otimes \left\{t^3\widehat{\mathbb{A}}_3^5 + ir^3\widehat{\mathbb{A}}_3^7\right\}\left\{t^4\widehat{\mathbb{A}}_3^2 + ir^4\widehat{\mathbb{A}}_3^4\right\}\mathbf{0}_3,\\
U_{3,2}\left\{|s_2\rangle \otimes \widehat{\mathbb{A}}_2^1\widehat{\mathbb{A}}_2^4\mathbf{0}_2\right\} &= |s_3\rangle \otimes \left\{t^3\widehat{\mathbb{A}}_3^1 + ir^3\widehat{\mathbb{A}}_3^3\right\}\left\{t^4\widehat{\mathbb{A}}_3^6 + ir^4\widehat{\mathbb{A}}_3^8\right\}\mathbf{0}_3,\\
U_{3,2}\left\{|s_2\rangle \otimes \widehat{\mathbb{A}}_2^3\widehat{\mathbb{A}}_2^4\mathbf{0}_2\right\} &= |s_3\rangle \otimes \left\{t^3\widehat{\mathbb{A}}_3^5 + ir^3\widehat{\mathbb{A}}_3^7\right\}\left\{t^4\widehat{\mathbb{A}}_3^6 + ir^4\widehat{\mathbb{A}}_3^8\right\}\mathbf{0}_3.
\end{aligned} \tag{20.6}$$

which should be compared with (20.4).

In this scenario, we find sixteen nonzero coincidence rates, each of the form $\Pr(\widehat{\mathbb{A}}_3^i\widehat{\mathbb{A}}_3^j\mathbf{0}_3|\Psi_0)$, where $i = 1, 3, 5, 7$ and $j = 2, 4, 6, 8$. All of them are independent of ϕ^1 and of ϕ^2. For example, $\Pr(\widehat{\mathbb{A}}_3^1\widehat{\mathbb{A}}_3^6|\Psi_0) = (t^1r^2t^3t^4)^2$, and so on. In the case of symmetrical beam-splitters, where $t^i = r^i = 1/\sqrt{2}$, all 16 rates are equal to $1/16$.

For FRANSON-2, the detectors behave in a manner consistent with the notion that photons are classical-like particles propagating along definite paths.

We should comment on the choice of stage diagram for FRANSON-2, as this impacts significantly on the encoding of program MAIN. Our choice of introducing detectors $5_3, 6_3, 7_3$, and 8_3 seems inevitable but puzzling, because it could be claimed that in a real experiment, there would only be four final stage detectors, not eight. However, our observation above that the long-arm photon signals could occur perhaps many years after the short-arm signals addresses that point: the observer will have real evidence that one set of signals has arrived long before the other set. The fact that the same atoms could persist in the configuration of detectors $1_3, 2_3, 3_3$, and 4_3 until they did service as detectors $5_3, 6_3, 7_3$, and 8_3 is irrelevant.

A related point is that, for simplicity, we chose to model all of the eight final-stage detectors to be associated with stage Σ_3, but that is not necessary. It would perhaps have been more logical to assign the long-arm detectors to a separate, later stage, but that would have been an inessential complication in programming that would make no difference to the calculations or to the conclusions drawn from them.

FRANSON-2 is an important illustration that the observer–apparatus side of quantum physics can contain real surprises. The next variant, FRANSON-3, is even more surprising.

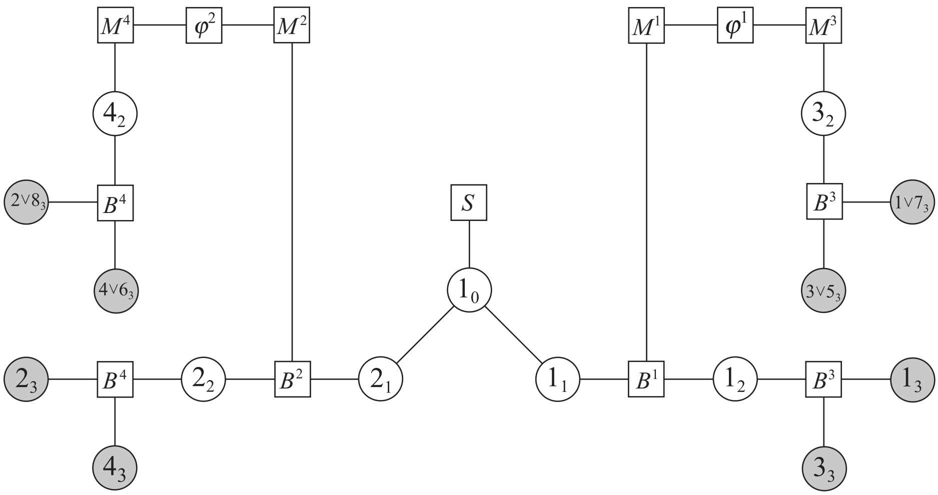

Figure 20.3. FRANSON-3: the Franson experiment for $\tau_2 \ll \Delta T \ll \tau_1$.

20.5 FRANSON-3: $\tau_2 \ll \Delta T \ll \tau_1$

This is the actual scenario discussed by Franson (Franson, 1989). In the following, S stands for "short path" and L for "long path." The fundamental change induced by the observer's setting of ΔT such that $\tau_2 \ll \Delta T \ll \tau_1$ is that, unlike the previous scenario, the observer cannot now use individual times of detector clicks to establish which of the coincidences S–S or L–L has occurred in a given run of the experiment. This presumes that a given run lasts at least as long as the coherence time, and that coincidence observations are being made at times greater than a critical time $\tau_c \equiv \tau_s + \Delta T$ into any given run. Here τ_s is the earliest time that a wave train following an S path could take to a stage Σ_3 detector. Coincidence observations of interference involving any L path at any time earlier than τ_c into a given run will not occur, simply because any wave train taking such a path would still be on its way to stage Σ_3 detectors.

FRANSON-3 is discussed and modeled assuming observations are made at times later than τ_c. In that regime, it will then not be possible for the observer to use detection times to distinguish between S–S correlations and L–L correlations. However, the observer will be able to filter out the two separate S–L correlations.

The relevant diagram is Figure 20.3, which is identical to Figure 20.2 except now 5_3 is replaced by $(3\vee 5)_3$, 7_3 is replaced by $(1\vee 7)_3$, 6_3 is replaced by $(4\vee 6)_3$, and 8_3 is replaced by $(2\vee 8)_3$, where for example $3\vee 5$ means "3 or 5." Which alternative is taken depends on the contextual information available in principle to the observer.

The dynamics for this scenario is identical to that for the previous one, except for the last equation in (20.6), which is replaced by

$$U_{3,2}\left\{|s_2\rangle \otimes \widehat{\mathbb{A}}_2^3 \widehat{\mathbb{A}}_2^4 \mathbf{0}_2\right\} = |s_3\rangle \otimes \left\{t^3\widehat{\mathbb{A}}_3^3 + ir^3\widehat{\mathbb{A}}_3^1\right\}\left\{t^4\widehat{\mathbb{A}}_3^4 + ir^4\widehat{\mathbb{A}}_3^2\right\}\mathbf{0}_3. \tag{20.7}$$

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With this amended information, program MAIN gives the following nonzero coincidence rates:

$$\begin{aligned} \Pr\left(\widehat{\mathbb{A}}_3^1\widehat{\mathbb{A}}_3^2\mathbf{0}_3|\Psi_0\right) &= \Pr\left(\widehat{\mathbb{A}}_3^3\widehat{\mathbb{A}}_3^4\mathbf{0}_3|\Psi_0\right) = \tfrac{1}{4}\cos^2\left(\tfrac{1}{2}\phi^1 + \tfrac{1}{2}\phi^2\right), \\ \Pr\left(\widehat{\mathbb{A}}_3^2\widehat{\mathbb{A}}_3^3\mathbf{0}_3|\Psi_0\right) &= \Pr\left(\widehat{\mathbb{A}}_3^1\widehat{\mathbb{A}}_3^4\mathbf{0}_3|\Psi_0\right) = \tfrac{1}{4}\sin^2\left(\tfrac{1}{2}\phi^1 + \tfrac{1}{2}\phi^2\right), \end{aligned} \tag{20.8}$$

and eight others that each have value 1/16, for the symmetric case $t^i = r^i = 1/\sqrt{2}$, $i = 1, 2, 3, 4$.

These results are a spectacular demonstration of temporal nonlocality as well as spatial non-locality: interference is occurring between S–S and L–L outcomes.

Note that in actual FRANSON-3 type experiments, the observer would have to measure the times at which coincidence clicks were obtained during each run and then post-select, that is, filter out, those coincidences corresponding to the $\{S\text{–}S,\ L\text{–}L\}$ processes and those corresponding to $\{S\text{–}L,\ L\text{–}S\}$.

20.6 Conclusions

Since the publication of Franson's original paper, there has been great interest in empirical confirmation of FRANSON-3 predictions. While there is still some room for debate concerning the interpretation of the experiment, the results of Kwiat et al. (1993) vindicate Franson's prediction, which corresponds to $\Pr(\widehat{\mathbb{A}}_3^1\widehat{\mathbb{A}}_3^2\mathbf{0}_3|\Psi_0) = \frac{1}{4}\cos^2(\frac{1}{2}\phi^1 + \frac{1}{2}\phi^2)$ in our approach.

Assuming the quantum theoretical interpretation of this experiment is correct, then there is an extraordinary lesson to be learned, not about systems under observation in particular, but about the rules concerning the use of apparatus and how these can differ spectacularly from those expected classically. The interference of the S–S and L–L amplitudes in FRANSON-3 cannot be envisaged in a classical way to occur locally in time. Any attempt to think about such interference in terms of photons as actual particles would lead to bizarre concepts that would never be acceptable conventionally. The conclusion is that a two-photon state is not equivalent under all circumstances to a state with two separate but entangled photons. A more recent quantum optics experiment with similar conclusions has been reported by Kim (Kim, 2003).

The weight of evidence points to the conclusion that quantum outcome amplitudes are dynamically correlated with *contextual information* held by the observer. When some information is absent, then quantum interference can occur. This supports the position of Heisenberg and Bohr concerning the fundamental principles and interpretation of quantum physics. Quantum optics experiments such as FRANSON are providing more and more evidence that QM is not just a theory of SUOs but also a fundamental perspective on the laws of observation in physics. It is our considered view that the surface of those laws has only been scratched to date.