ON EMISSION LIFETIMES IN ATOMIC CASCADE TESTS OF THE BELL INEQUALITY

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It is shown that the possibility of subluminal information exchanges cannot be ruled out in atomic cascade tests of the Bell inequality, if the emission lifetimes of both photons of the cascade are taken into account.

Eight atomic cascade experiments [1–8] have been performed so far in order to test Bell-type inequalities and comprehend the contradiction between quantum mechanics and local realism. The experimental evidence is in favor of quantum mechanics, against the whole class of local realistic theories, although the "anomalous" result of Holt and Pipkin [2] has not been explained yet. An interesting tentative analysis in this direction was performed a few years ago by Pappalardo and Rapisarda [9], but it seems to have triggered little interest in the scientific community. On the other hand it is well known that, at present, the only local explanation of the experimental results is via the denial of the so-called no-enhancement hypothesis (see ref. [10] and references therein).

In this note we wish to avoid following the "compulsory path" of investigating the validity and the reach of eventual additional assumptions, like the no-enhancement hypothesis, and we argue that in all the atomic cascade experiments so far performed, there is time enough for a subluminal signal to be exchanged between the polarizers and the source. We will do this by "revisiting" Pappalardo and Rapisarda's paper, with the introduction of a new element: the emission lifetime of the first photon of the atomic cascade.

In a typical atomic cascade experiment [1–8], a source S emits correlated photons which travel in nearly opposite directions and cross a filter and a polarizer before being detected by a photomultiplier (see fig. 1).

The filter λ_i selects the wavelength of the ith photon of the atomic cascade so that, say, the first photon of a couple is always detected in the left-hand side of the apparatus. Let L_i be the distance between the source and the ith polarizer. Usually (but not always [11]) $L_1 = L_2$. We will consider in the follow-

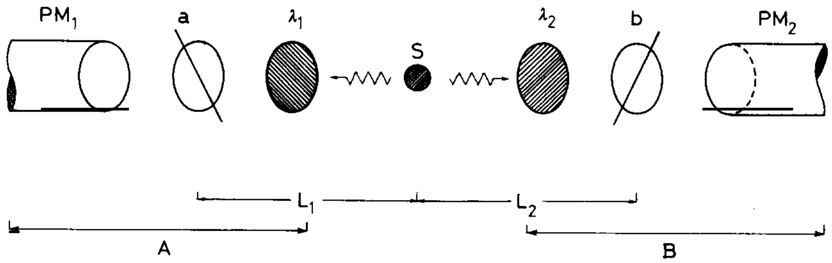

Fig. 1. A typical test of the Bell inequality with atomic cascades.

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ing, for the sake of simplicity, the case $L_1 = L_2 = L$, and will focus our attention on the Orsay experiments [5–7]. Our question is: which percentage of correlated photon pairs can have information about the polarizers' settings?

From a realistic standpoint the photon's polarization is created together with the photon itself, at the instant of its emission. But then: can the experimental setup influence the photon's polarization? And if yes, how? This is an extremely complex question, going far beyond the purpose of this Letter, and therefore we will limit ourselves to simple models in which the atom "explores" its environment by sending a (subluminal) signal that comes back with some information. For instance an atom prepared in a well-defined excited state at time $t=0$ can be informed of the presence of a polarizer at a distance L only at times $t \geqslant 2L/c$. As a consequence, the photon's polarization can be influenced by the polarizer's setting only if the photon is emitted at $t \geqslant 2L/c$. As far as one considers that the intermediate state in an atomic cascade is a well-defined state, "prepared" by the first photon's emission, the above considerations allow us to infer that a second photon of a cascade cannot have any information about the polarizers' settings if it leaves the atom at a time $t < 2L/c$ after the first photon's emission. The probability for this to happen is:

$$R_2 = \int_0^{2L/c} \exp(-t/\tau_2) \frac{\mathrm{d}t}{\tau_2} = 1 - \exp(-2L/c\tau_2) , \qquad (1)$$

where τ_2 is the lifetime of the intermediate atomic level. In the Orsay case $L = 6$ m and a$\tau_2 = 5$ ns, so that

$$R_2^{\mathrm{Orsay}} = 0.9997 . \qquad (2)$$

Therefore, only 0.03% of the second photons can be informed about the polarizers, and this is the reason why not much attention has been paid to this problem so far. The situation will be very different when also the emission of the first photon of the couple will be considered. But before doing this, let us shed some light on some of the ideas this calculation bears on.

(i) *The problem of time-dependence of the emission.* We shall not discuss here the problem of the validity of the exponential dependence of the emission probability, except for the following point: what is the meaning of $t=0$ in eq. (1)? According to quantum mechanics this is related to the wave-packet collapse that takes place at the instant of the last observation: If we "observe" the above-mentioned atom at the time $t = t^*$, and we still find it in the excited state, then we are forced to rewrite the decay probability in the form $\exp[-(t-t^*)/\tau_2]$, namely, we have to redefine the time origin in agreement with out last observation, and no importance is to be attached to the exponential law $\exp(-t/\tau_2)$ *before* the observation. We will not linger here about the paradoxical features of the wave-packet collapse. Suffice it to say that $t=0$ in eq. (1) stands for the instant of emission of the *first* photon, whatever this means. On the other hand, when considering the cascade process as a whole, in the following formulae, $t=0$ will stand for the time of excitation of the atom in the upper level of the cascade; for instance, in the Orsay case, $t=0$ will be the excitation time of the Ca-atom to the $4p^2\,{}^1S_0$-state from the ground state, by the well-known two-photon absorption.

(ii) *Information exchange between polarizer and atom.* It has been assumed, when writing (1), that a photon cannot have any information about the polarizers' settings if it leaves the atom at $t < 2L/c$. This is of course a rather naive picture of the emission process: a photon does not even exist before being emitted and, strictly speaking, one should speak of the atom itself having or not having information about the polarizers. But then, how can an atom interact or exchange information with its environment if it does not emit any photon? A logical possibility would be by the wavefunction of the atom itself, and an example is given for instance in ref. [12], in which it is shown, in the case of two interacting atoms, that the photon emission probability does depend on the interatomic distance. Therefore an excited atom "feels" the presence of another atom (and in general of its surroundings) via its wavefunction, without emitting any photon. A similar mechanism is here suggested: we are considering the possibility that an excited atom that is going to emit two correlated photons, might get information about the two polarizers before emitting one or both photons.

Let us tackle now the general case: let t_1 (t_2) be the emission time of the first (second) photon of the cascade, and τ_1, τ_2 the respective lifetimes. We have to require that both $t_1 < 2L/c$ and $t_2 < 2L/c$ in order to exclude the possibility that some information about the polarizers comes back to the atom before the *second* photon has been emitted.

The probability for a second photon to be emitted before it can exchange any information with either polarizer is

$$R_2'(t_1) = \int_{t_1}^{2L/c} \exp[(t_2 - t_1)/\tau_2] \frac{dt_2}{\tau_2}$$

$$= 1 - \exp[-(2L/c - t_1)/\tau_2] , \quad \text{if } t_1 \leqslant 2L/c ,$$

$$= 0 , \quad \text{otherwise} ,$$

where we require, of course, $t_1 > 0$. And the probability that, given a couple, neither photon can have any information about the two polarizers is [#1]

$$R = \int_0^\infty \frac{dt_1}{\tau_1} \exp(-t_1/\tau_1) R_2'(t_1)$$

$$= 1 - \exp(-2L/c\tau_1) \frac{\tau_1}{\tau_1 = \tau_2}$$

$$- \exp(-2L/c\tau_2) \frac{\tau_2}{\tau_2 - \tau_1} . \quad (3)$$

In the Orsay experiment $L = 6$ m, $\tau_1 = 89$ ns, $\tau_2 = 5$ ns, so that

$$R^{\text{Orsay}} = 0.324 . \quad (4)$$

In conclusion, only 32.4% of the photon couples are "clean" in the Orsay case. For the remaining 67.6%, information-exchange mechanisms, of the type suggested in (ii), are quite possible.

A glance at formulae (2) and (4) makes us understand why this problem has been overlooked up to now. In every experiment so far performed, only τ_2 has been considered: the coincidence window, the signal-to-noise ratio, and even the switching time in the third Orsay experiment [7] are settled on the lifetime of the *second* photon of the couple. The first photon plays only the role of "trigger" in the detection mechanism. In ref. [7], for instance, one reads: "In this experiment, switching between the two channels occurs about each 10 ns. Since this delay, as well as the lifetime of the intermediate level of the cascade (5 ns), is small compared to L/c (40 ns) [#2], a detection event on one side and the corresponding change of orientation on the other side are separated by a spacelike interval". And also: "The settings are changed during the flight of the particles". The problem of the first photon's lifetime τ_1 is not even considered (the coherence length of this first photon is $c\tau_1 = 26.7$ m. Note that $L = 6$ m), and since $R_2^{\text{Orsay}} \approx 1$ (formula (2)), possibilities of the type (ii) are completely neglected.

Is the low value of R (formula (4)) just a feature of the Orsay experiment, or is it a common characteristic of all the atomic cascade tests of Bell's inequality? The answer is given in table 1, from which it can be inferred that in the other experiments the situation is even worse, the percentage of "clean" couples being even lower than in the Orsay case. The last experiment, performed at Stirling [8], uses the two-photon decay of metastable atomic hydrogen from the $2S_{1/2}$ to the $1S_{1/2}$ state. The upper state $2S_{1/2}$ has the lifetime $\tau \approx \frac{1}{8}$ s and decays primarily by the simultaneous emission of two photons: therefore we applied here the same analysis as in the atomic cascade experiments with $\tau_1 = 0.125$ s and $\tau_2 = 0$. The experimental values of the lifetimes in table 1 have been taken from ref. [14].

The low values of R in table 1 open a new interesting door for local and realist tentative explanation of the EPR puzzle. In fact, if $1 - R$ of the photon couples might have information about the polarizers' settings and if this information could, say, "enhance" some particular photon polarization already in the source, the experimental results would be liable to a local reinterpretation; some problems may arise in connection with the third Orsay experiment, but Zeilinger has recently found a beautiful "loophole" that is able to dodge its overwhelming result against local realist theories [15]. It is interesting to note that Zeilinger's idea is also interlinked with time in the analysis of the experiment.

Another possible source of controversy concerns a perhaps less-known Orsay result: in ref. [11] Aspect claims that the distance between source and po-

[#1] We are assuming here a double exponential law for the double photon emission. For a quantum electrodynamical analysis of this, see ref. [13].

[#2] In ref. [7] L is defined as the distance between the two analyzers ($L = 12$ m) whilst in this paper L is the distance source–analyzer ($L = 6$ m).

Table 1

Ref. exp.	Atom	Cascade	τ_1 (ns)	τ_2 (ns)	L (m)	R
[1]	Ca	$4p^2\,{}^1S_0$–$4s4p\,{}^1P_1$–$4s^2\,{}^1S_0$	89	5	0.5	0.010
[2]	Hg	$9\,{}^1P_1$–$7\,{}^3S_1$–$6\,{}^3P_0$	–	48	0.07	<0.010 [a]
[3]	Hg	$9\,{}^1P_1$–$7\,{}^3S_1$–$6\,{}^3P_0$	–	48	0.5	<0.067 [a]
[4]	Hg	$7\,{}^3S_1$–$6\,{}^3P_1$–$6\,{}^1S_0$	46	114	–	0.001 [b]
[5–7]	Ca	$4p^2\,{}^1S_0$–$4s4p\,{}^1P_1$–$4s^2\,{}^1S_0$	89	5	6	0.324
[8]	D	$2S_{1/2}$–$1S_{1/2}$	0.125×10^9	0	–	0

[a] Calculated with $\tau_1=0$.
[b] Calculated with $L=0.5$ m.

larizers has no influence on the correlation function. Actually, Aspect observes no significant change in the coincidence rates if the polarizer in B (see fig. 1) is put close to the source or at the distance $L=6$ m from it. We stress that only L_2 has been varied in the Orsay experiment and that it is not an easy task to generalize eq. (3) to the case $L_1\neq L_2$ because some hypotheses would be required on how the information-exchange mechanism takes place (for instance: does a filter prevent information exchanges if it does not "match" the emission wavelength of the excited atom in the source?). We will not consider here the case $L_1\neq L_2$ and the theoretical consequences it might entail, and will just observe that even if *both* polarizers are put close to the source, this does not influence R (eq. (3)) too much, due to the long lifetime τ_1 in the Orsay case. Some values of $R^{\mathrm{Orsay}}(L)$ are given in table 2. Note that it is necessary to take L as large as twice the coherence length of the first photon ($L=2c\tau_1=53.4$ m) in order that 98% of the couples be "clean".

We wish to conclude this note with a remark: the sensible criticism put forward by Caser [16] and Marshall [17] about the smallness of eventual coincidence-window effects of the type proposed by one of us in ref. [18] seems to be less effective now due to the rather big values of τ_1 and/or τ_2 in table 1. It is worth stressing that in ref. [18] only the lifetime $\tau_2=5$ ns of the $4s4p\,{}^1P_1$–$4s^2\,{}^1S_0$ Ca-transition was considered, and this is the *shortest lifetime* appearing in table 1. Bell-inequality violations would be much more facile if also τ_1 were introduced in coincidence-window analyses of the experiment.

Table 2

L (m)	$R^{\mathrm{Orsay}}(L)$
2	0.092
4	0.215
6	0.324
12	0.569
24	0.824
48	0.971

In conclusion, we suggest that subluminal information exchanges cannot be ruled out in atomic cascade tests of Bell's inequality, if the first lifetime of the cascade is also taken into account. It is therefore proposed that in future experiments, like for instance the one in preparation at Catania [19], tests on the influence of variations of L_1 and/or L_2 on the coincidence rate should be performed. This will probably require special devices in order to reach larger source-polarizer distances; this might be achieved by inserting large refraction-index materials in the photons' optical paths.

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