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# Loophole–free four photon EPR experiment

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## Abstract

A loophole–free four photon EPR experiment requiring only 67% detection efficiency which prepares independent photons into a non–maximal singlet–like spin state by means of an asymmetrical beam splitter is proposed. The experiment does not suffer from the usual poor net detection efficiency and can therefore serve to close the low detection efficiency, the *no enhancement*, and the spacelike separation loophole.

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Recently the Bell issue of disproving local as well as nonlocal hidden–variables theories has witnessed a renewed interest primarily because of two new techniques. One is the usage of the fourth order interference for local [1–7] as well as non–local [8] hidden–variables theories and the other is the recent improvement in the efficiencies of single–photon detectors [9]. That might permit a conclusive Einstein–Podolsky–Rosen experiment. An experiment with maximally entangled photons can hardly be used for the purpose because it requires at least 83% detection efficiency [10] and the appropriate detectors are still not available. (83% being an overall detection efficiency, the "appropriate" detectors mean the ones with over 90% detector efficiency.) Therefore, Eberhard turned to nonmaximally entangled photons and showed that for them only 67% detection efficiency is required. [11] He obtained his result by employing an asymmetrical form of the Bell inequality for which he found angles of polarizers for maximal values of the background that violated this Bell inequality for given efficiency $\eta$. Kwiat, Eberhard, Steinberg, and Chiao [3] then used the result to make a proposal for a loophole–free Bell inequality experiment, i.e., a Bell experiment without additional assumptions which is an ultimate aim of Bell experiments since the very beginning of the local reality issue. [12] In this paper we show that the coincidence probabilities obtained by the fourth order interference at an asymmetrical beam splitter violate the usual Clauser–Horne–like form of the Bell inequality with only 67% detection efficiency. This shows that the afore–mentioned Eberhard's asymmetrical form of the Bell inequality and the background level he introduced are not essential for obtaining his result. Instead of the background level one can use other parameters—in our case the reflectivity of a beam splitter—and instead of an asymmetrical form of the Bell inequality one can use the usual symmetric form. In addition, it is shown that, contrary to a widespread persuasion [3], a loophole–free Bell experiment by means of two down–converted photons interfering at a symmetric beam splitter is possible but with at least 86% detection efficiency. We also show that in the proposal of Kwiat, Eberhard, Steinberg, and Chiao [3] the method of application of Eberhard's result by means of attenuating one of the beams incoming to a beam splitter runs into unpredicted problems. Therefore we propose a four photon experiment which dispenses with attenuation and prepares two independent photons in a *pure* nonmaximal singlet–like state instead. The preparation boils down to a projection on the four dimensional Hilbert subspace of this singlet state carried out by actual recording of the other two (of four) photons, thus solving the low detection efficiency, the *no enhancement* [12–14], and the spacelike separation loophole.

The paper is organized in the following way. First, the formalism of the fourth order interference at an asymmetrical beam splitter is briefly introduced in the plane wave presentation. It serves us to formulate a symmetric Clauser–Horn–like as well as the asymmetric Eberhard's form of the Bell inequality and to show them equal and being violated starting with 67% detection efficiency. At the same time we show that the birefringent analyzers separate photons emerging from the same side of the beam splitter in such a way to enable a conclusive violation of the Bell inequality already with 86% detection efficiency. Then we show in which ways one can achieve a perfect control over photons emerging from the beam splitter using two nonlinear type–II crystals. In the end we dwell on our four photon proposal which enables one to prepare two of the four photons as *Bell pairs* (singlet states) by recording coincident counts of the other two photons at an asymmetrical beam splitter.

To describe the behaviour of the photons at a beam splitter in the spin space we follow the results obtained in Pavičić [5,6]. The signal and idler down–converted photons emerging from a nonlinear crystal [see Fig. 1)] are parallelly polarized [1] and because we aim at an entangled photon state we must use a polarization rotator for one of the beams. We set the rotator at $90^0$ to obtain the maximal number of photons emerging from the opposite sides of the beam splitter as compared with those emerging from the same sides. The signal and idler photons have no definite relative phases. So, there is no interference of the second order but only of the fourth order which we describe in the second quantization formalism using plane waves. [5] The state of incoming polarized photons is $|\Psi\rangle = |1_x\rangle_1 |1_y\rangle_2$ . The actions of beam–splitter BS, polarizer P1, and detector D1 are taken into account by the following outgoing electric field operators:

$$\hat{E}_1 = (\hat{a}_{1x} t_x \cos\theta_1 + \hat{a}_{1y} t_y \sin\theta_1)\, e^{i\mathbf{k}_1\cdot\mathbf{r}_1 - i\omega(t-t_1-\tau_1)}$$
$$+ i\,(\hat{a}_{2x} r_x \cos\theta_1 + \hat{a}_{2y} r_y \sin\theta_1)\, e^{i\tilde{\mathbf{k}}_2\cdot\mathbf{r}_1 - i\omega(t-t_2-\tau_1)}\,, \tag{1}$$

where $t_x^2$ is transmittance, $r_x^2$ is reflectance, $t_j$ is time delay after which photon $j$ reaches BS, $\tau_1$ is time delay between BS and D1, and $\omega$ is the frequency the photons. The annihilation operators act as follows: $\hat{a}_{1x}|1_x\rangle_1 = |0_x\rangle_1$, $\hat{a}_{1x}|0_x\rangle_1 = 0$. $\hat{E}_2$ is defined analogously. Until we arrive at our four photon proposal below, we limit ourselves to this idealized model because the analysis of any specific, real experiment would involve complications irrelevant to the questions of interest. For a realistic elaboration of Eqs. (1), (2), (3), (5), etc., by means of wave packets we refer the reader to Reff. [4,6]. We only stress here that these equations remain unchanged insomuch as all experimental parameters—in effect the lowered *visibility*—are absorbed by $\eta$ and $\cos\phi$ below.

The probability of joint detection of two ordinary photons by detectors D1 and D2 is

$$P(\theta_1,\theta_2) = \langle\Psi|\hat{E}_2^\dagger \hat{E}_1^\dagger \hat{E}_1 \hat{E}_2|\Psi\rangle = A^2 + B^2 - 2AB\cos\phi\,, \tag{2}$$

where $A = t_x t_y \cos\theta_1 \sin\theta_2$, $B = r_x r_y \sin\theta_1 \cos\theta_2$, and $\phi = (\tilde{\mathbf{k}}_2 - \mathbf{k}_1)\cdot\mathbf{r}_1 + (\tilde{\mathbf{k}}_1 - \mathbf{k}_2)\cdot\mathbf{r}_2 = 2\pi(z_2 - z_1)/L$, where $L$ is the spacing of the interference fringes (see Fig. 1). $\phi$ can be changed by moving the detectors transversely to the incident beams as indicated by '$\leftrightarrow$' in Fig. 1. If we now introduce $s = t_x t_y (t_x^2 t_y^2 + r_x^2 r_y^2)^{-1/2}$ and $r = \frac{r_x r_y}{t_x t_y}$ and assume positioning of detectors so as to have $\phi = 0$, probability (2) reads

$$P(\theta_1,\theta_2) = \eta^2 s^2 (\cos\theta_1 \sin\theta_2 - r \sin\theta_1 \cos\theta_2)^2\,, \tag{3}$$

where $\eta$ is the (detector) efficiency. The probability tells us that the photons appear to be in an *entangled* state whenever they emerge from two different sides of BS.

The probability of one ordinary and one extraordinary photon being detected by D1 and D2$^\perp$ (as enabled by birefringent polarizer P2) is given by

$$P(\theta_1,\theta_2^\perp) = \eta^2 s^2 (\cos\theta_1 \cos\theta_2 + r \sin\theta_1 \sin\theta_2)^2\,. \tag{4}$$

The singles–probability of detecting one photon by D1 and the other going through P2 and through either D2 or D2$^\perp$ without necessarily being detected by either of them [obtained by summing up Eqs. (3) and (4) and multiplying them by $\eta$ for D1–detection] is

$$P(\theta_1,\infty) = \eta s^2(\cos^2\theta_1 + r^2\sin^2\theta_1)\,, \tag{5}$$

$$\text{and analogously :}\qquad P(\infty,\theta_2) = \eta s^2(\sin^2\theta_2 + r^2\cos^2\theta_2)\,. \tag{6}$$

The singles–probability of detecting one photon by D1 and the other going through P1 and D1 is (assuming $t_x = t_y$)

$$P(\theta_1\times\theta_1) = \frac{\eta s^2 r}{2}\sin^2(2\theta_1)\,. \tag{7}$$

Let us see the effect of these results on possible violations of, first, a Clauser–Horne–like form and, secondly, Eberhard's form of the Bell inequality: $B \le 0$. In the Clauser–Horne form $B$ is defined so as to satisfy [see Eqs. (3), (5), and (6)]

$$\eta s^2 B_{CH} \equiv P(\theta_1,\theta_2) - P(\theta_1,\theta_2') + P(\theta_1',\theta_2') + P(\theta_1',\theta_2) - P(\theta_1') - P(\theta_2) \le 0\,, \tag{8}$$

where $P(\theta_1') = P(\theta_1',\infty)$ and $P(\theta_2) = P(\infty,\theta_2)$, as given by Eqs. (5) and (6). $B$ of the Eberhard's form is, in effect, defined so as to satisfy [see Eqs. (3–5)]

$$\eta s^2 B_E \equiv P(\theta_1,\theta_2) - P(\theta_1',\theta_2') - P(\theta_1,\theta_2'^{\perp}) - P(\theta_1'^{\perp},\theta_2) - (1-\eta)[P(\theta_1) + P(\theta_2)] \le 0\,, \tag{9}$$

where $(1-\eta)P(\theta_1)$ is the probability of one photon being detected by D1 and the other reaching either D2 or D2$^\perp$ but not being detected by them due to their inefficiency.

Either of the above two forms contains terms which depend on $\eta$ only linearly, i.e., which relies on firing of only one of the two detectors under consideration. If we were able to make a device which would assure that photons almost always reach detectors (in all previous experiments under 15% of photons passed the pinholes of the detectors) and fire them according to their $\eta$'s, we would have a loophole–free experiment (with $\eta > 0.67$), i.e., an experiment without additional assumptions (e.g., the *no enhancement* assumption

[12,13]). In the last part of the paper we propose such a device using four photons of which two put the other two almost always through the pinholes of the detectors (which then react or do not react according to their efficiency $\eta$).

Here, let us assume that we already do have such a source and that photons always reach detectors upon emerging from the beam splitter. Then we have two possibilities: either both photons sometimes exit the same side of the beam splitter or they never do so. If they never do (as, e.g., in the experiment of Kwiat at al. [3]), with birefringent polarizers we can have a perfect *"control"* over the photons in the sense that, e.g., when detector D1 is being triggered (and D1$^\perp$ did not react) we immediately know the conjugate photon finished either in D2 or in D2$^\perp$. If the photons exit the same port sometimes, then only with a detector which could tell two photons from one would be able to tell whether the conjugate photon finished in D1 or in either D2 or D2$^\perp$. (Such detectors are theoretically possible [15] but are still not in use.) If we use detectors which cannot tell one photon from two (all experiments with beam splitters carried out so far used such detectors) we shall call the photons taking part in the experiment *uncontrolled* photons because a click of D1 can mean that the conjugate photon finished in either D2 or D2$^\perp$ but can also mean that both photons finished in D1. The latter counts obviously do not belong to our statistics but we can nevertheless try to see whether the Bell inequality can be violated even with such "intruder" counts. These counts correspond to the probabilities given by Eq. (7) and when we introduce them [adding them to the singles probabilities given by Eq. (6)] into Eqs. (8) and Eq. (9) we obtain the following stronger Bell inequalities for *uncontrolled* photons:

$$B'_{CH} = B_{CH} - r[\sin^2(2\theta'_1) + \sin^2(2\theta_2)]/2 \le 0\,, \tag{10}$$

$$B'_{E} = B_{E} - r[\sin^2(2\theta_1) + \sin^2(2\theta_2)]/2 \le 0\,, \tag{11}$$

We now compare the two forms of the Bell inequality first for *controlled* photons [Eq. (8) and Eq. (9)] and then for *uncontrolled* photons [Eq. (10) and Eq. (11)].

As for *controlled* photons we obtain $Max[B](r,\eta)$ surfaces (by a computer optimization) for both forms (8) and (9). As we can see in Fig. 2, there is no difference between them. The differences are $10^{-5}$ in average, for 100 iterations used in numerical calculations of maxima. The angles for the two forms are, of course, not equal. The values above the $B = 0$ plane mean violations of the Bell inequality. For $r = 1$ we obtain $Max[B] = 0$ for $\eta = 0.828427$ in accordance with the result of Garg and Mermin. [10] For $r \to 0$ we obtain a violation of the Bell inequality for any efficiency greater then 66.75%. Thereupon, we calculate $\eta$, first from $B_{CH} = 0$ and then from $B_E = 0$. Again, [see Fig. 3] there is no difference between the two forms. As an example, the Bell inequality given by Eq. (8) is violated for $r = 0.33$, $\eta = 0.76$, $\theta_1 = 118°$, $\theta_{1'} = 85°$, $\theta_2 = 5°$, and $\theta_{2'} = 152°$.

As for *uncontrolled* photons we compare Eqs. (10) and (11). Both equations are violated in the same way—starting with 85.8% efficiency—in opposition to the widespread belief that "unless the detector can differentiate one photon from two... no indisputable test of Bell's inequalities is possible." [3] Of course, when collecting counts of D1 for singles probabilities $P(\theta_1)$ one has to discard the counts obtained in coincidence with $D1^\perp$. One obtains the latter coincidence using birefringent polarizers. The efficiencies for uncontrolled photons are shown as the upper curve in Fig. 3. Once again, there is no difference between the forms. To give an example, the "stronger" Bell inequality given be Eq. (10) is violated for $r = 1$, $\eta = 0.9$, $\theta_1 = 32°$, $\theta_{1'} = -6°$, $\theta_2 = 96°$, and $\theta_{2'} = 58°$.

The afore–mentioned *control* of all photons can be achieved automatically if photons never emerge from the same side of a beam splitter and this is what Kwiat, Eberhard, Steinberg, and Chiao [3] aimed at. We obtain their Mach–Zehnder–like set–up by substituting the nonlinear crystal in Fig. 1 with two type–II crystals (MZ–II inset in Fig. 1) which down–convert collinear and orthogonally polarized signal and idler photons of the same average frequencies (half of the pumping beam frequency). The cones of signal and idler photons just touch each other along the outgoing pumping beam and this is the direction wherefrom we take signal and idler photons. The crystals are pumped by a 50:50 split laser beam (filtered out before signal and idler photons reach detectors) whose intensity is accommodated so as to give only one down–conversion at a chosen time–window. Since one cannot tell which crystal a down–converted pair is coming from, the state of the photons incoming at the beam splitter must be described by the following superposition

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|1_x\rangle_1|1_y\rangle_1 + f|1_x\rangle_2\,|1_y\rangle_2\right)\,, \tag{12}$$

where $0 \le f \le 1$ describes attenuation of the lower incoming beam.

The joint D1–D2 probability is given [in an analogous way as in Eq. (2)] by

$$P(\theta_1,\theta_2) = \frac{\eta^2}{2}[\cos\theta_1\sin\theta_2(t_x r_y + f\,t_y r_x\cos\phi) + \sin\theta_1\cos\theta_2(t_y r_x + f\,t_x r_y\cos\phi)]^2\,. \tag{13}$$

The probability of both photons emerging from either the upper or the lower side of BS is for $\phi = 180^\circ$ (+) and $\phi = 0^\circ$ (−) given, respectively, by

$$P(\infty\times\infty) = \frac{\eta^2}{2}[(t_x t_y \pm f r_x r_y)^2 + (r_x r_y \pm f t_x t_y)^2]\,. \tag{14}$$

It is obvious from this equation that for the crosstalk $t_x = r_y = 1$ no photons emerge from the same sides of the beam splitter (because of the relations $t_x^2+r_x^2 = 1$ and $t_y^2+r_y^2 = 1$ and their consequence: $t_y = r_x = 0$). For $\phi = 180^\circ$ (−) and $\phi = 0^\circ$ (+) Eq. (13) yields

$$P(\theta_1,\theta_2) = \frac{\eta^2}{2}(\cos\theta_1\sin\theta_2 \pm f\sin\theta_1\cos\theta_2)^2\,. \tag{15}$$

These two equations give the same $Max[B]$ surface as also shown in Fig. 2.

Now Kwiat, Eberhard, Steinberg, and Chiao [3] claim that the crosstalk is not necessary for $\phi = 0^\circ$ ( [3], p. 3215, 1st col., last ¶). However, that would require that the conditions $r_x r_y = f t_x t_y$ and $t_x t_y = f r_x r_y$ from Eq. (14) be simultaneously satisfied what is clearly impossible for $f < 1$. Thus, the only way to make use of $f < 1$ for either $\phi = 0^\circ$ or $\phi = 180^\circ$ is the crosstalk $t_x = r_y = 1$ and this is apparently difficult to control within a measurement. [3] Besides, the problem of both photons reaching detectors (i.e., passing their pinholes) remains unsolved. We therefore propose another *set–up* which dispenses with attenuation and the *no enhancement* assumption and which resolves the problem of both photons reaching detectors.

Schematic of the proposed experiment is given in Fig. 4. Two afore–discussed Mach–Zehnder–like set–ups, MZ–II 1 and MZ–II 2, fed by a split laser beam act as two independent sources of two independent singlet pairs. As shown above, photons emerge only from the opposite sides of the second beam splitter of MZ–II 1 and MZ–II 2. Two photons from each pair interfere at the beam splitter, BS, of the *event–ready preselector* (see Fig. 4) and as a result the other two photons, under particular conditions elaborated below, appear to be in a nonmaximal singlet state although the latter photons are completely independent and nowhere interacted. The state of the four photons immediately after leaving MZ–II 1 and MZ–II 2 is

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|1_x\rangle_{1'}|1_y\rangle_1 \;-\; |1_y\rangle_{1'}|1_x\rangle_1) \otimes \frac{1}{\sqrt{2}}(|1_x\rangle_{2'}|1_y\rangle_2 \;-\; |1_y\rangle_{2'}|1_x\rangle_2) \,. \tag{16}$$

The probability of detecting all four photons by detectors D1, D2, D1', and D2' is thus

$$P(\theta_{1'},\theta_{2'},\theta_1,\theta_2) = \langle\Psi|\hat{E}^\dagger_{2'}\hat{E}^\dagger_{1'}\hat{E}^\dagger_2\hat{E}^\dagger_1\hat{E}_1\hat{E}_2\hat{E}_{1'}\hat{E}_{2'}|\Psi\rangle = \frac{1}{4}(A^2+B^2-2AB\cos\phi)\,, \tag{17}$$

where $\hat{E}_1, \hat{E}_2$, and $\phi$ are as given above, $\hat{E}_{j'} = (\hat{a}_{j'x}\cos\theta_{j'} + \hat{a}_{j'y}\sin\theta_{j'})e^{-i\omega'_j t_{j'}}$; $j = 1, 2$; $A = Q(t)_{1'1}Q(t)_{2'2}$ and $B = Q(r)_{1'2}Q(r)_{2'1}$; here $Q(q)_{ij} = q_x \sin\theta_i\cos\theta_j - q_y\cos\theta_i\sin\theta_j$.

The assumed 100% visibility here is of course an oversimplification since a detection cannot be carried out at a point (see Fig. 1) but only over a detector width $\Delta z$. Therefore, in order to obtain a more realistic probability we integrate Eq. (17) over $z_1$ and $z_2$ over $\Delta z$ to obtain

$$\begin{aligned} P(\theta_{1'},\theta_{2'},\theta_1,\theta_2) &= \frac{1}{4}\int_{z_1-\Delta z/2}^{z_1+\Delta z/2}\int_{z_2-\Delta z/2}^{z_2+\Delta z/2}\Big[A^2+B^2-2AB\cos[2\pi(z_2-z_1)/L]\Big]dz_1dz_2 \\ &= \frac{1}{4}(A^2+B^2-v2AB\cos\phi)\,, \end{aligned} \tag{18}$$

where $v = [\sin(\pi\Delta z/L)/(\pi\Delta z/L)]^2$ is the *visibility* of the coincidence counting. With detector pinhole width $\Delta z \approx 0.1$ one would obtain $v \approx 0.95$ which in real experiments reduces further to about 0.8 but that can be improved to 0.9. [16] So, the visibility itself is not a problem once all photons reach detectors no matter whether they fire them or not (because of detector inefficiency). What was the biggest problem in the two photon experiments carried out so far was exactly that photons mostly did not reach detectors at all, i.e., that they had a rather poor net detection efficiency which was always below 10%. The reason is that one cannot enlarge the pinholes in front of the detectors behind a beam splitter—that would destroy the interference fringes. In our design, however, we use D1 and D2 to record only those coincidence counts which really activate their counters. Whenever only D1 or only D2 fires we discard all the corresponding data. So, we use the coincidence counts at BS to prepare the other two photons into a *Bell pair* (singlet state). They enable us to adjust pinholes *ph* (see Fig. 4) for the latter photons so as to form solid angles appropriately bigger than the pinholes of D1, D1$^\perp$, D2 and D2$^\perp$ do. According to Eqs. (17) and (18) pinholes *ph* are not needed at all but this is an oversimplified ideal case. In a real experiment *ps*'s must be adjusted so as not to let through photons of slightly different frequency from other unaccounted downconverted pairs. On the other hand, in a real experiment one has to take into account that the probability of only one of *MZ–II*'s in Fig. 4 emitting two photon pairs is not negligible. In order to get rid of the latter counts when recording singles events, e.g., D1', we first discard all data corresponding to the firing of both D1' and D1'$^\perp$ detectors. Then we have to get rid of possible two photons firing D1'. We can do this by splitting possible two–photon 1' wave packet across an additional beam splitter and symmetrically positioned two detectors on each of its sides. [2] Alternatively, we can do a real experiment by using photons of different colours in a scheme which eliminates the possibility of having two pairs emitted from one of the sources. [17] Let us in the end see how the *event ready* preparation works.

Term 1/4 in Eq. (18) refers to firing of D1 and D2. Other 3/4 refer to D1 and D2$^\perp$, D1$^\perp$ and D2, and D1$^\perp$ and D2$^\perp$. So, to get the probability of firing of D1' and D2' gated (see Fig. 4) by firing of D1 and D2 we have to multiply the equation by 4: $P(\theta_{1'},\theta_{2'}) = 4\,P(\theta_{1'},\theta_{2'},\theta_1,\theta_2)$. For $\phi=0^\circ$, $\theta_1=90^\circ$, $\theta_2=0^\circ$, and $v\to 1$, Eq. (18) yields the following nonmaximal singlet–like probability which permits a perfect control of photons $1'$ and $2'$:

$$P(\theta_{1'},\theta_{2'}) = \eta^2 s^2 (\cos\theta_{1'}\sin\theta_{2'} - r\sin\theta_{1'}\cos\theta_{2'})^2\,. \tag{19}$$

This means that D1 and D2—while detecting coincidences—act as event–ready selectors [12] and with the help of a gate (see Fig. 4) we can extract those $1'$ and $2'$ photons that are in a non–maximal singlet state, take them miles away, and carry out a loophole–free Bell experiment by means of P1', D1', D1'$^{\perp}$, P2', D2', and D2'$^{\perp}$ with only 67% efficiency in the limit $r \to 0$. Then one can use fast optical switches to close the spacelike separation loophole.

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# FIGURES

FIG. 1. Beam splitter set–up and Mach–Zehnder–like set–up (when inset MZ–II is put in place of NL; according to Ref. [9]). As birefringent polarizers P1 and P2 may serve Nicol, Glan–Thompson or Wollaston prisms (which at the same time filter out the uv pumping beam in case of MZ–II).

FIG. 2. The surface $Max[B] = Max[B_{CH}] = Max[B_E]$ [Eqs. (8) and (9)] for the optimal angles of the polarizers. All the values above the $B = 0$ plane violate the Bell inequality $B \leq 0$.

FIG. 3. Lower plot: $\eta$'s as obtained for $B = B_{CH} = B_E = 0$ from Eqs. (8) and (9). Upper plot: $\eta$'s as obtained for $B' = B'_{CH} = B'_E = 0$ from Eqs. (10) and (11).

FIG. 4. Proposed experiment. Detectors D1, D1$^\perp$, D2 and D2$^\perp$ and their counters serve as the event–ready preselector. MZ–II 1 and MZ–II 2 are Mach–Zehnder–like devices (shown in Fig. 1) that serve as sources of singlet pairs. As birefringent polarizers P1' and P2' may serve Wollaston prisms (which at the same time filter out the uv pumping beam). Pinholes *ph* form considerably bigger solid angles than the pinholes of D1, D1$^\perp$, D2 and D2$^\perp$.

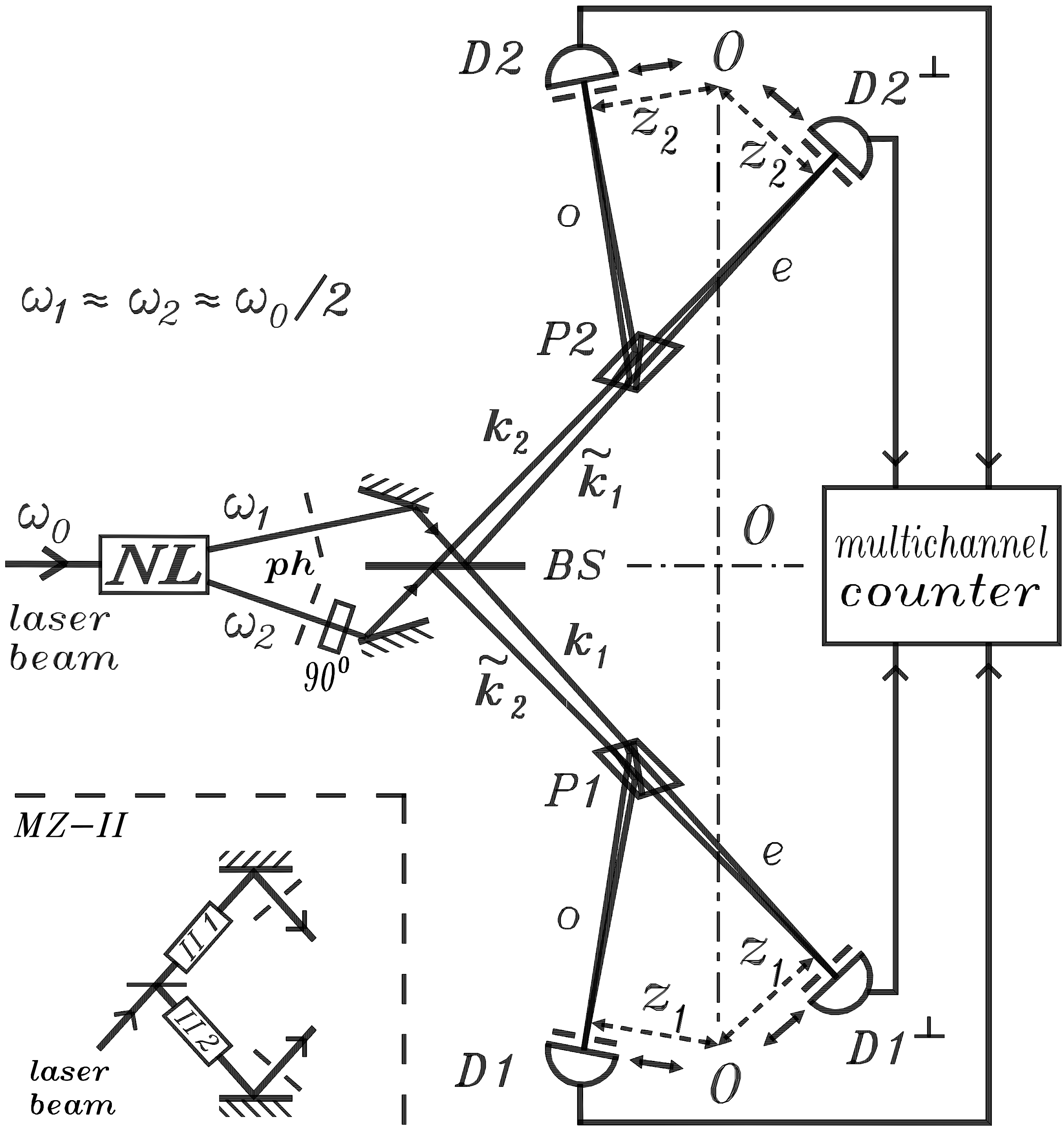
D2
O
D2⊥
z2
z2
o
e
ω1 ≈ ω2 ≈ ω0/2
P2
k2
k̃1
ω0
ω1
NL
ph
BS
O
multichannel
counter
laser
beam
ω2
90⁰
k1
k̃2
P1
MZ−II
e
o
z1
z1
laser
beam
D1
O
D1⊥

*Fig. 1*

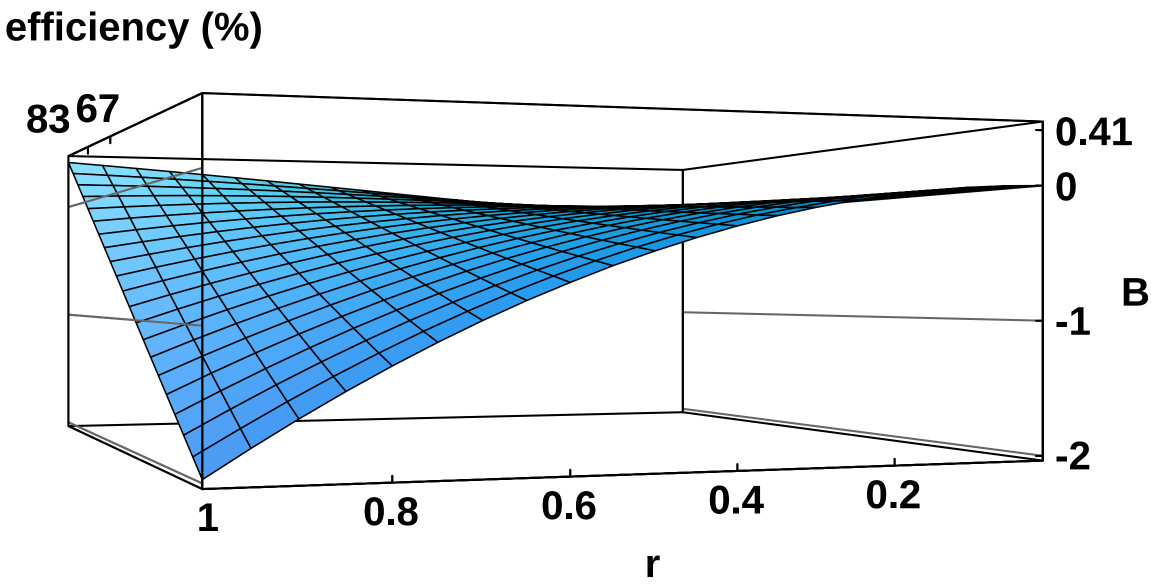


Fig. 2

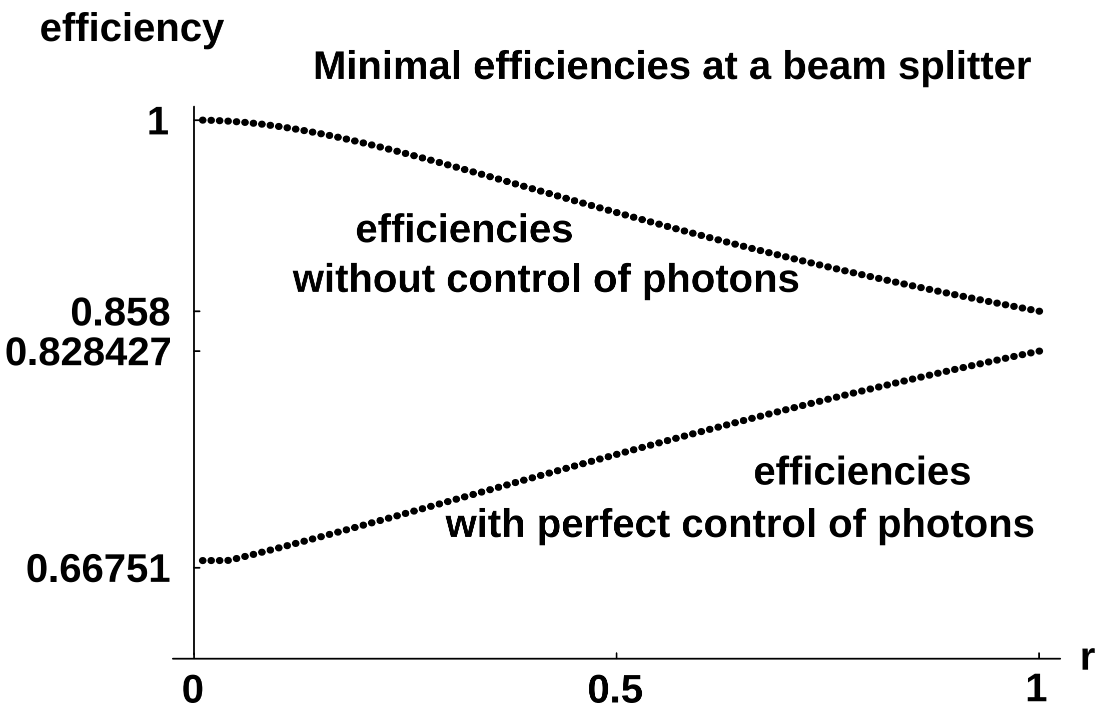
efficiency
Minimal efficiencies at a beam splitter
1
0.858
0.828427
0.66751
efficiencies
without control of photons
efficiencies
with perfect control of photons
0
0.5
1
r

Fig. 3

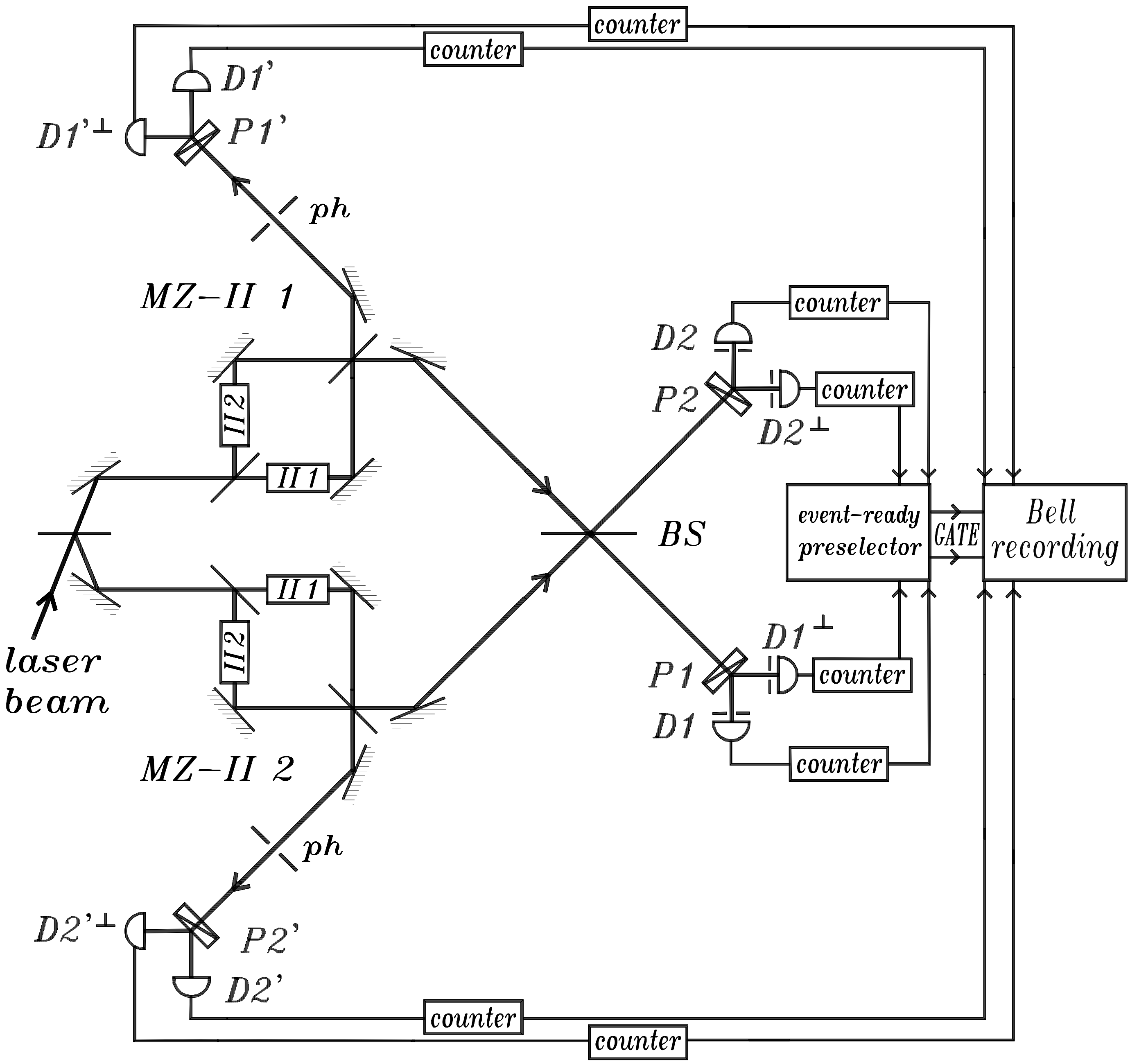
counter
counter
D1'
D1'⊥
P1'
ph
MZ–II 1
II 2
II 1
laser
beam
II 1
II 2
MZ–II 2
ph
D2'⊥
P2'
D2'
counter
counter
counter
D2
P2
counter
D2⊥
BS
event–ready
preselector
GATE
Bell
recording
D1⊥
P1
counter
D1
counter

*Fig. 4*