

NUCLEAR PHYSICS. PARTICLE PHYSICS. ASTRO-PARTICLE PHYSICS

QUANTUM CROSSING SYMMETRY AS HEART OF GHOST  
IMAGING. GHOST IMAGING MISTERY DISCOVERED?

D. B. ION<sup>1</sup>, M. L. D. ION<sup>2</sup>, L. RUSU<sup>1</sup>

<sup>1</sup>*Institute for Physics and Nuclear Engineering, Department of Fundamental Physics, POB MG 6,  
Bucharest, Romania*

<sup>2</sup>*Bucharest University, Department for Nuclear Physics, POB MG 11, Bucharest, Romania*

(Received November 17, 2008)

*Abstract.* In this paper it is shown that the keys of the ghost imaging mistery are the crossing symmetric photon reactions in the nonlinear media. Then, the intuitive mechanism for the description of the ghost imaging in terms of the quantum mirror (QM) is reviewed. Moreover, it is proved that the QM-laws depend only on the energy-momentum conservation and not on the photons entanglement.

*Key words:* ghost imaging, crossing symmetry, quantum mirrors, spherical quantum mirrors.

## 1. INTRODUCTION

In 1995, at Baltimore University, professor (Dr.) Yanhua Shih initiated ghost-imaging research [1], by using entangled photons. In that experiment, one photon passed through stenciled patterns in a mask to trigger a detector, and another photon was captured by a second detector. Surprisingly, an image of the pattern between the two detectors appeared, which the physics community called ghost-imaging. Some definitions of ghost imaging (see refs. [1–4]) are as follows: (i) Ghost-imaging is a visual image of an object created by means of light that has never interacted with the object. (ii) Ghost imaging is an unusual effect by which an image is formed using light patterns that do not emanate from the target object. (iii) Ghost imaging, is a novel technique in which the object and the image system are on separate optical paths. (iv) “Ghost-imaging is similar to taking a flash-lit photo of an object using a normal camera. The image is formed by the photons that come out of the flash, bounce off the object, and then are focused through the lens onto photoreactive film or a charge-coupled array. But, in this case, the image is not formed from light that hits the object and bounces back,” Dr. Shih said. “The camera collects photons from the light sources that did not hit the object, but are paired through a quantum photons are recorded”.

Here, we must underline that ten years ago, based on the crossing symmetry of the SPDC-photon reactions, the authors of the papers [5–6] presented a new interpretation of all the ghost phenomena (ghost imaging, ghost interference and ghost diffraction). Then, they introduced the concept of SPDC-quantum mirror (QM) and on this basis they proved some important QM-physical laws which can be of great help for a more deep understanding of the ghost imaging phenomena.

This article is aimed at exploring and analyzing the quantum nature of ghost imaging. It is true that classical challenges have never stopped. Quantum? Classical? A hot debate (see Ref. [4]) is currently focused on ghost imaging. This article defends the quantum mechanical point of view based on quantum crossing symmetric photon interactions proposed ten years ago in the papers [5, 6]. By this we show that the heart of the ghost imaging can be the “quantum crossing symmetric interactions” (quantum-CSI).

## 2. CROSSING SYMMETRIC SPDC-PROCESSES AS A NEW KIND OF “ENTANGLEMENT”

In quantum field theory crossing symmetry is a symmetry that relates S-matrix elements. Interaction processes involving different kinds of particles can be obtained from each other by replacing incoming particles with outgoing antiparticles after taking the analytic continuation. The crossing symmetry applies to all known particles, including the photon which is its own antiparticle. For example, the annihilation of an electron with a positron into two photons is related to an elastic scattering of an electron with a photon by crossing symmetry. This relation allows to calculate the scattering amplitude of one process from the amplitude for the other process if negative values of energy of some particles are substituted.

$$\gamma + e^- \rightarrow e^- + \gamma \quad (1)$$

$$e^- + e^+ \rightarrow \gamma + \gamma. \quad (2)$$

By examination, it can be seen that these two interactions are related by crossing symmetry. It could then be said that the observation of Compton scattering implies the existence of pair annihilation and predicts that it will produce a pair of photons.

The first experiments on ghost imaging were performed using a pair of entangled photons produced by spontaneous parametric down conversion (SPDC). In this process, a primary pump (p) photon is incident on a nonlinear crystal and produces the photons idler (i) and signal (s) by the reaction:  $p \rightarrow s + i$ . These photons are correlated in energy, momentum, polarizations and time of birth. Some of these features, such as energy and momentum conservations:  $\omega_p = \omega_s + \omega_i$ ,

$\vec{k}_p = \vec{k}_s + \vec{k}_i$  are exploited to match in diverse experiments (*e.g.*, Momentum conservation in the “degenerate” case when the idler and the signal photons acquire the same frequency leads to the production of a pair of simultaneous photons that are emitted at equal angles relative to the incident beam). Now, if the S-matrix crossing symmetry [7] of the electromagnetic interaction in the spontaneous parametric down conversion (SPDC) crystals is taken into account, then the existence of the direct SPDC process (see Fig. 1).

$$\gamma_p \rightarrow \gamma_s + \gamma_i \quad (3)$$

will imply the existence of the following crossing symmetric processes

$$\gamma_p + \bar{\gamma}_s \rightarrow \gamma_i, \quad (4)$$

$$\gamma_p + \bar{\gamma}_i \rightarrow \gamma_s, \quad (5)$$

as real processes which can be described by the same transition amplitude. Here, by  $\bar{s}$  and  $\bar{i}$  we denoted the time reversed photons relative to the original photons  $s$  and  $i$ , respectively.

In fact, the SPDC-effects (4)–(5) can be identified as being directly connected with the  $\chi^{(2)}$  – second-order nonlinear effects called in general three wave mixing. So, the process (3) is just the inverse of second-harmonic generation, while, the effects (4)–(5) corresponds to the emission of optical phase conjugated replicas in the presence of pump laser via three wave mixing. Here some remarks are necessary in connection with the entanglement. If the quantum entanglement is a quantum mechanical phenomenon in which the quantum states of two or more objects have to be described with reference to each other, even though the individual objects may be spatially separated, then the crossing symmetry of an interaction can be interpreted as a more geneneral kind of entanglement.

### 3. GHOST IMAGING VIA SPDC-CROSSING SYMMETRIC PHOTON REACTION

The main purpose here is to obtain an answer to the basic question: *Is ghost imaging mystery discovered via the quantum mirror (QM)?* So, we start with a short review of the quantum mirror definition and QM-physical laws [5–6].

SPDC-QUANTUM MIRROR (QM) (see Fig. 1). A quantum mirrors is called SPDC-QM if is based on the quantum SPDC phenomena (3)–(5) in order to transform signal photons, characterized by  $(\omega_s, \vec{k}_s, \vec{e}_s, \mu_s)$ , into idler photons with  $(\omega_p - \omega_s, \vec{k}_p - \vec{k}_s, \vec{e}_s^*, -\mu_s) \equiv (\omega_i, \vec{k}_i, \vec{e}_i, \mu_i)$ . Therefore, according to the schematic description from Fig. 1, a SPDC-QM is composed from: a high quality

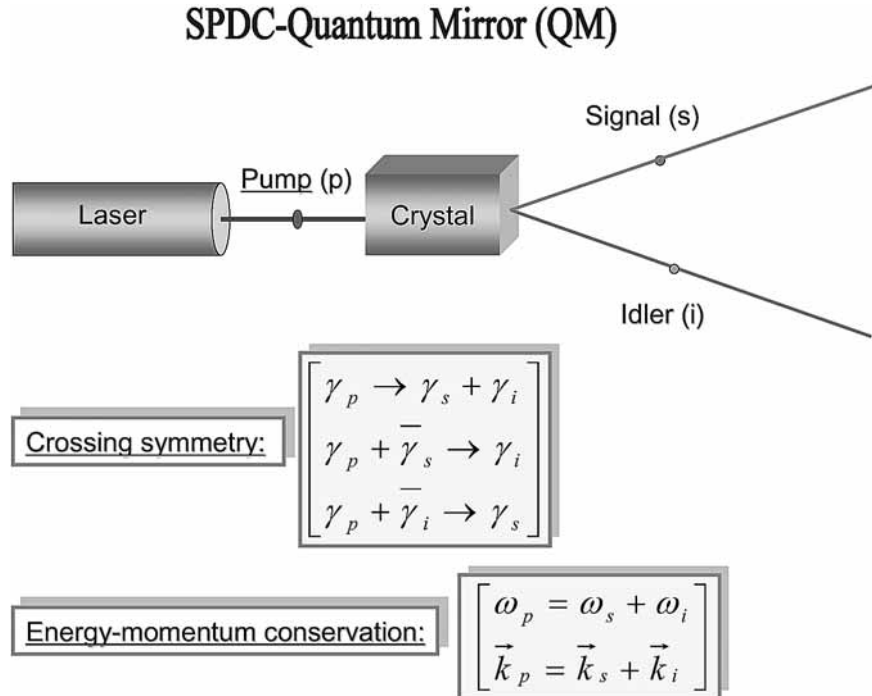


Fig. 1 – A schematic description of a SPDC-QM.

*laser pump* (p), a *transparent crystal* in which all the *three photon reactions* (3)–(5) can be produced, all satisfying the same *energy-momentum conservation laws*:  $\omega_p = \omega_s + \omega_i$ ,  $\vec{k}_p = \vec{k}_s + \vec{k}_i$ .

In these conditions a new geometric optics can be developed on the basis of the concept of quantum mirrors (QM). Hence, the laws of the plane quantum mirror (see Fig. 2a) and that of spherical quantum mirror (SQM) (see Fig. 2b), observed in the ghost imaging experiments [2–3], are proved as natural consequences of the energy-momentum conservation laws. By the QM-mechanism (see Fig. 1) the objects and their images can be considered as being on the same optical paths. Therefore, the key of ghost imaging mystery can be given by the electromagnetic crossing symmetric photon reactions (3)–(5). Indeed, in the case of ghost imaging observed in the paper [2] the ghost image is produced as follows (see Fig. 1a): The image forms indirectly from the signal photons that come out of the flash, bounce off the object, and then are focused through the lens onto QM where they are transformed in idler photons  $\mathbf{i}_s$  which are collected in the idler dedector. So, in this case, the image is not formed directly from signal photons that hits the object and bounces back. The image is formed only by idler  $\mathbf{i}_s$ -photons from QM-sources that did not hit the object, but are obtained via crossing symmetric photon reaction (4) and not via photon reaction (3).

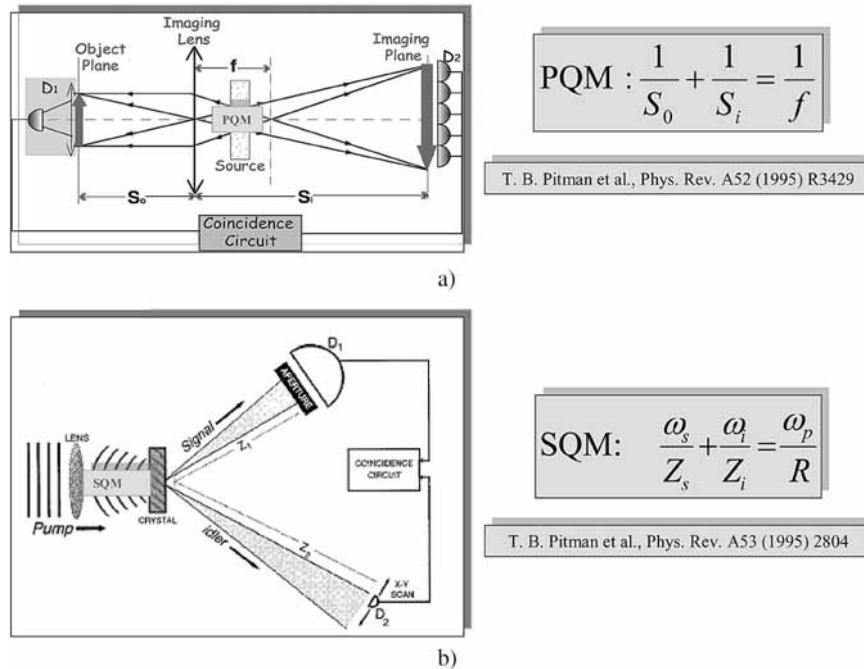


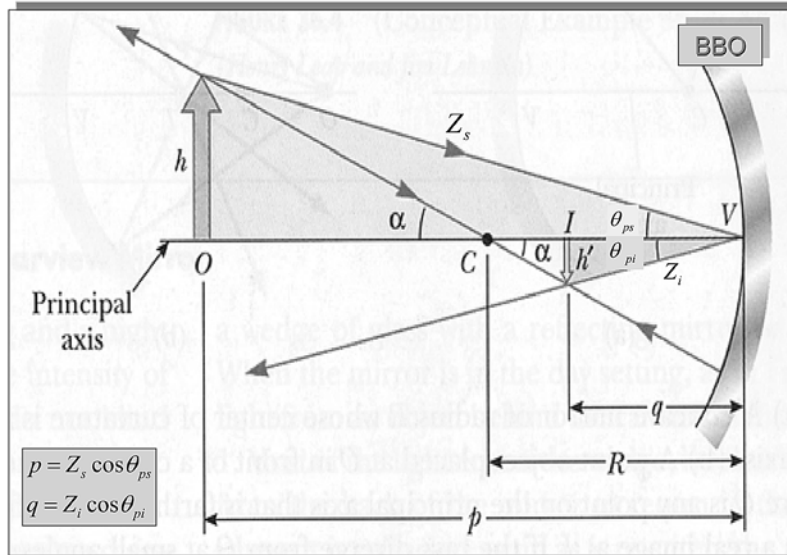
Fig. 2 – Laws of: a) PQM and b) SQM.

Clearly, a SPDC crystal illuminated by a high quality laser beam can act as real quantum mirrors since by the crossing processes (4) (or (5)) a signal photon (or idler photon) is transformed into an idler photon  $i_s$  (or signal photon  $s_i$ ), respectively. The quantum mirrors can be “plane quantum mirrors” (PQM) (Fig. 2a) and “spherical quantum mirrors” (SQM) (Fig. 2b) according to the character of incoming laser waves (plane waves or spherical waves). In order to avoid many complications, in this presentation we will work only in the thin crystal approximation. Now, it is important to note that using the QM-concepts [5,6] the results PQM and SQM from Fig. 2 are obtained only as a consequence of the energy-momentum conservation (or phase matching conditions) without any kind of photon entanglement. In order to illustrate this we presented in Fig. 3 a short proof of SQM-law.

Also, it is important to remark that, the high quality of the SPDC-QM is given by the following peculiar characteristics [5–6]:

- (i) *Coherence*. The SPDC-QM preserves high coherence between s-photons and i-photons;
- (ii) *Distortion undoing*. The SPDC-QM corrects all the aberrations which occur in signal or idler beam path;
- (iii) *Amplification*. A SPDC-QM amplifies the conjugated wave if some conditions are fulfilled.

### Law of Spherical Quantum Mirror



a)

### A proof of SQM-Law

(I) $\frac{\omega_s \cos \theta_{ps}}{p} + \frac{\omega_i \cos \theta_{pi}}{q} = \frac{\omega_s \cos \theta_{ps} + \omega_i \cos \theta_{pi}}{R}$	$(I_p) \frac{\omega_s}{p} + \frac{\omega_i}{q} = \frac{\omega_p}{R}$
(II) $M = \frac{h'}{h} = -\frac{q \omega_s \cos \theta_{ps}}{p \omega_i \cos \theta_{pi}}$	$(II_p) M = \frac{h'}{h} = -\frac{q \omega_s}{p \omega_i}$

From  $\vec{k}_p = \vec{k}_s + \vec{k}_i$  we have  
 (1a)  $\omega_s \sin \theta_{ps} = \omega_i \sin \theta_{pi}$   
 since  
 (1b)  $n_r \sin \theta_{pr}^m = \sin \theta_{pr}, r = s, t$

Now, using angles defined in Fig.2, we have  
 (2)  $\sin \theta_{ps} = \frac{h \cos \theta_{ps}}{p}, \sin \theta_{pi} = -\frac{h' \cos \theta_{pi}}{q}$   
 Then, from Eqs. (2), we obtain  
 (3)  $-\frac{h'}{h} = \frac{q \omega_s \cos \theta_{ps}}{p \omega_i \cos \theta_{pi}}$   
 Next, from Fig.3, we get  
 (4)  $\tan \alpha = \frac{h}{p-R} = -\frac{h'}{R-q}$   
 Finally, by combining (3) with (4)  
 (5)  $-\frac{h'}{h} = \frac{R-q}{p-R} = \frac{q \omega_s \cos \theta_{ps}}{p \omega_i \cos \theta_{pi}}$   
 from which we get the results (I) - (II).

b)

Fig. 3 – a) A schematic description of the SQM; b) a short proof of the SQM-law.

(iv) *Very high selectivity.* In the QM-mechanism the energy-momentum conservation law acts as a daimon which select only the imaging photons  $i_s$  which are produced by the crossing symmetric photon reaction (4).

Finally, we note that in Refs. [5–6] is also presented an answer to the following very important question: Can the QM-principle produce a new revolution in the optical devices?

#### 4. DISCUSSIONS AND CONCLUSIONS

The main results and conclusions underlined in this paper can be summarized as follows:

(i) The class of SPDC-phenomena (3) is enriched by introducing the crossing symmetric processes (4)–(5) as real phenomena described just by the same transition amplitude as that of the original SPDC-process (4) and satisfying the same energy-momentum conservation law (see Fig. 1).

(ii) The ghost-imaging is similar to taking a flash-lit photo of an object using a normal camera. The image forms indirectly from the signal photons that come out of the flash, bounce off the object, and then are focused through the lens onto QM where they are transformed in idler photons  $i_s$ , which are collected on the photoreactive film or a charge-coupled array. So, in this case, the image is not formed directly from signal photons that hits the object and bounces back. The image is formed only by idler  $i_s$ -photons from QM-sources that did not hit the object, but are obtained via crossing symmetric photon reaction (4) and not via photon reaction (3).

(iii) The essential results on ghost imaging is that the QM-Laws from Fig. 2 are dependent only on the energy-momentum conservation law and not on entanglement (see the proof of SQM-law in Fig. 3).

Finally, we think that the future goals must be to delve deeply into the QM-physics of the ghost-imaging phenomenon, complete the QM-theory of that QM-technology and to improve the technique toward practical, QM-imaging applications.

The type of ghost imaging physics demonstrated at ARL [8] may help lead to improved satellite imaging of the earth's surface and better imaging of targets through partially obscuring smoke and clouds as well as improved communication of images. Some other potential uses for this ghost imaging quantum camera include improved x-rays and higher resolution endoscopy.

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