Journal of Quantitative Spectroscopy & Radiative Transfer 178 (2016) 66–76

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

Review

Violation of a Bell-like inequality by a combination of Rayleigh scattering with a Mach–Zehnder setup

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ARTICLE INFO

Article history:
Received 4 August 2015
Received in revised form
9 September 2015
Accepted 9 September 2015
Available online 10 October 2015

Keywords:
Bell-like inequality
CHSH-inequality
Rayleigh scattering
Mach–Zehnder interferometry

ABSTRACT

In this paper I propose a classical optics experiment that results in a maximum violation of a Bell-like inequality. The first part is concerned with the Bell-like inequality (the so-called CHSH-inequality) itself. Its importance and its maximum violation in Quantum Mechanics (QM) are discussed in detail by employing an abstract probability state concept in a 4-dim. but classical event space. A T-matrix that represents the integral part of a corresponding Green's function as well as a statistical operator that contains a negative quasi-probability can be related to the corresponding quantum mechanical experiment. It is demonstrated that the derivation and usage of the T-matrix and the Green's function is equivalent to what is known from classical scattering theory. It is shown moreover that the negative quasi-probability of the statistical operator may be interpreted as a sink of probabilities related to two single events of the considered 4-dim. event space. A necessary condition for the violation of the CHSH-inequality is derived and discussed afterwards. In the second part of this paper I discuss a modification of the 4-dim. event space considered in the first part. It is shown that a combination of conventional Rayleigh scattering with a Mach–Zehnder setup would be able to put this modification into practice. Thus it becomes possible to achieve a maximum violation of the CHSH-inequality, if formulated in terms of intensities, on a pure classical way. The combination of classical light scattering with correlation experiments such as proposed in this paper may open new ways to study and to use the violation of Bell-like inequalities in modern optics.

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http://dx.doi.org/10.1016/j.jqsrt.2015.09.002

1. Introduction

In 1964 J.S. Bell published his famous paper regarding the just as well famous Einstein–Podolsky–Rosen (EPR) paradox – a paradox that had been discussed since 1935 until Bell's paper purely on a philosophical level [1]. EPR is concerned with the question if QM can be considered to be a complete theory, or if we have to search for any hidden parameters to complete it [2,3]. In his paper Bell derived an inequality, formulated in terms of correlations, for a certain class of experiments. He proved that this inequality cannot be violated by any of such experiments or any theory of local realism. The term "local" in this context expresses the fact that there is no "spooky" action at a distance between two distant measurement locations. And that a measurement is "realistic" means that the property of an object we intend to measure can be related to this object independent of whether we perform the measurement or not. Or, in other words: "The moon is there even when not being observed". Today it is tacitly assumed that any classical theory (Newtonian mechanic, Electrodynamic, etc.) belong to a theory of local realism. And, moreover, the impossibility of any such theory to violate Bell's inequality holds independent of whether there exist hidden parameters or not. 5 years later, in 1969, J. Clauser, M. Horne, A. Shimony, and R. Holt published an alternative inequality – the so-called CHSH-inequality [4]. Since then this inequality has become a much-cited relation. A first experiment to demonstrate its violation in QM was put into practice in 1982 by A. Aspect and co-workers. They used polarization entangled photons to create a 4-dim. event space [5]. Several other quantum mechanical experiments have been developed in the meantime. They are of growing importance not only for questions regarding the foundations of QM but also in quantum information theory (e.g., quantum cryptography and quantum computing), and in quantum optics. Today, the violation of the CHSH-inequality in QM is accepted among most of the physicists as an experimental fact. It is assumed that this violation expresses the non-local character of this theory, and, more important, that it is exactly this non-local character that makes QM essentially differ from our classical lines of thought. The following two representative quotations are meant to emphasize this point of view:

Bell's theorem, which states that the prediction of quantum theory cannot be accounted for by any local theory, represents one of the most profound developments in the foundation of physics [6].

Because quantum mechanics violates Bell's inequality, it is in empirical disagreement with the family of local physical theories [7]

These and similar quotations reflect the position that the CHSH-inequality provides us with a bound of any related correlation experiment if performed with a classical setup. However, there is still an ongoing discussion regarding the possibility to violate Bell's inequality with a classical experiment. In 2010 Borges et al. performed a classical optics experiment that results in a maximum violation of a Bell-like (or CHSH-like) inequality if formulated in terms of intensities [8]. It is based on non-separable spin-orbit modes of a laser beam. In what follows I propose an alternative classical optics experiment that will also result in a maximum violation of the CHSH-inequality.

In the first part of this paper the CHSH-inequality and its maximum violation by a corresponding quantum mechanical experiment are discussed. An abstract probability state concept in a 4-dim. but classical event space is introduced to this end. Using a T-matrix will allow us to describe the experiment in terms of a basis transformation, as it is known from classical scattering theory [11]. It turns out that this T-matrix represents the decisive element of the interaction part of a corresponding Green's function. The existence of two sets of different basis vectors can be considered to be the result of two local and independent interaction mechanisms described on the level of the initially introduced abstract probability states. A statistical operator with negative quasi-probabilities can moreover be related to this experiment. The existence and meaning of such negative probabilities are other aspects of ongoing discussions in QM [9,10]. Here it is shown that the negative quasi-probabilities may be considered as a redistribution of (always positive) probabilities related to each single event of the 4-dim. event space. A necessary condition for the violation of the CHSH-inequality is derived and discussed afterwards. It is used as a proof that the classical counterpart of the quantum mechanical experiment will never be able to violate the CHSH-inequality.

The second part of this paper is concerned with the description of a classical optics experiment that will result in a violation of the CHSH-inequality if formulated in terms of intensities. For this we have to discuss an appropriate modification of the 4-dim. event space presented in the first part of this paper. It is finally shown that a combination of conventional Rayleigh scattering with a Mach–Zehnder setup would be able to accomplish this modification on a pure classical way. Thus it is demonstrated that it is questionable to relate the violation of Bell-like inequalities exclusively to the realm of QM without any reference to the experimental context. The violation of Bell-like inequalities with such classical experiments is moreover an indication that we have to revisit our understanding of "non-local theories". However, classical correlation experiments such as performed in [8] or proposed in this paper may open new ways to study and to use the violation of Bell-like inequalities in modern optics. Correlation measurements can be applied in a similar manner as known from scattering experiments, for example. i.e., the deviation from an initially given correlation or a combination of correlations can be used to gain information about the disturbance that causes this deviation. The CHSH-inequality – especially if used with parameter sets resulting in a maximum violation – is just one example that provides us with such an initial combination of correlations.