Statistical Identification for Generating Information Processes of Interference Patterns

László Nádai

RESUME OF NEW SCIENTIFIC RESULTS

Theses

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Introduction

Whether a photon is a particle or a wave? – this question has been raised for decades. For a long time it seemed that such questions have only historic interest and would be forgotten, since both qualities can be shown with a proper experimental arrangement, further, quantum optics is capable of describing both properties of the photon.

But in the last two decades the development of laser metrology (and certain measurements in particle physics made it possible to detect low intensity light and particle beams. Problems such as the *Einstein–Podolsky–Rosen paradox* were raised again, because it could not longer been stated that "The measurement is applied to a statistical sample."

It was first pointed out by Einstein, Podolsky and Rosen in a classic paper (1935) that according to the usual interpretation of quantum mechanics there exist certain two-particle states with the property that a measurement of one chosen variable of particle *A* completely determines the outcome of a measurement of the corresponding variable of particle B. At the time of measurement, the two particles may be so far apart that no influence resulting from one measurement can possibly propagate to the other particle in the available time.

According to Einstein, when the outcome of a measurement of some particle variable can be predicted with certainty, without disturbing the particle, then "... there exists an element of physical reality corresponding to this physical quantity ... ". In other words, then *particle* B *really has this value of the variable*, irrespective of whether it is actually measured or not. This must be contrasted with the quantum point of view, according to which the measurement creates the reality, in a sense. On the other hand, suppose that a different variable, say one that is canonically conjugate to the previous one, is measured for particle A. Then this predeterminates the value of the conjugate variable for particle B, and by the foregoing arguments particle B really *has* this value of the conjugate variable. But, if the two variables are canonical conjugates, then according to quantum mechanics they do not commutate and they can not both have definitive values at the same time. Now the decision whether to measure one or the other conjugate variable of particle A can be made when the two particles are far apart and can not communicate in the available time, yet it influences the state of particle B. We appear to have a contradiction which led Einstein to conclude that quantum mechanics is 'incomplete'.

Such counter-intuitive non-local correlations have, however, been observed experimentally (Aspect et al., 1982). The phenomenon is sometimes referred to as a *violation of Einstein locality*, and its implications have been widely discussed (Bohm, 1952; Bell, 1964; Clauser et al., 1969).

Attempts have been made to account for the predicted (and later observed) correlations between two particles in terms of *hidden variables*, or unmeasurable parameters that are supposed to determine the outcome of an experiment, but it was later shown by Bell and others that such non-local effects are fundamentally quantum mechanical, and that no realistic local theory can account for the correlation quantitatively.

Arthur Fine's (1982) approach resolves the contradiction between the violation of Bell-type inequalities and the assumption that the EPR experiment can be accommodated in a relativistic and deterministic universe. According to the so-called "Prisms Model" all probabilities can be interpreted as relative frequencies in a well-defined ordinary statistical ensemble. The "quantum probabilities", too, obtain a meaningful explanation inside of the classical Kolmogorovian theory of probability.

Research Objectives

Our attention was turned to observing and modelling an optical process which is capable of producing *measurable interference*, because interference is probably the simplest complex problem in quantum optics where the aforementioned aspects are simultaneously present. It is also an important point that the arrangement of the experiment is technically easy, and the measuring device can be clearly described theoretically – even classically.

The world-famous mathematician and theologian René Descartes (1596–1650) in his book *Discourse on the Method* formulated four simple rules that should be followed by anyone who is seeking for (scientific) truth:

> *The first was never to accept anything for true which I did not clearly know to be such; that is to say, carefully to avoid precipitancy and prejudice, and to comprise nothing more in my judgement than what was presented to my mind so clearly and distinctly as to exclude all ground of doubt.*
>
> *The second, to divide each of the difficulties under examination into as many parts as possible, and as might be necessary for its adequate solution.*
>
> *The third, to conduct my thoughts in such order that, by commencing with objects the simplest and easiest to know, I might ascend by little and little, and, as it were, step by step, to the knowledge of the more complex; assigning in thought a certain order even to those objects which in their own nature do not stand in a relation of antecedence and sequence.*
>
> *And the last, in every case to make enumerations so complete, and reviews so general, that I might be assured that nothing was omitted.*

Accepting these advises the research was split into four main stages beforehand.

1. First of all, an extensive *survey of literature* should be carried out for paradoxical phenomena in weak intensity beam interference, outlining the attempts that have been made to account for these phenomena, in order to propose a "new" paradigm for resolving the apparent contradictions.

2. Next, the *experimental apparatus* should be designed that was divided into parts according to the logic of input/output modelling: the statistics of the incoming photonic signal process should be characterized, the arrangement that produce interference should be described theoretically, and the parts of the output measurement unit should be examined.

3. For up to this point only (first- or higher-order) *correlations*, coincidences and momentums had been measured, the model for the photonic signal process (based on the results of stochastic control theory) was not involved. I intended to base my investigation theoretically on stochastic dependencies between absorption processes in the elements of the detector array. As the interference picture (that is the average intensity distribution) can not be interpreted after the impact of a few photons, this paradox can be lift by applying *double stochastic* vector processes, which are well-known from modern probability theory. Moreover, I can give a statistical characterization for the dynamics of absorption time (events of photon detection) vector processes by assuming the existence of stochastic connection with "hidden" generating information processes.

4. Finally, I should be aware that despite of all goodwill and every attempts that were made to complete the task, there is a limited relevance of the results and, of course, there are topics that are treated only cursorily or not at all. I should try to recognize these deficiencies, and to mark directions for further research.

NEW RESULTS

THE MAIN CONTRIBUTIONS of the dissertation are summarized as follows (with cross-references to the sections of Thesis).

THESIS 1. (Sections 3.3 and 7.2). *I proposed the application of vector-valued doubly stochastic Poisson process models for the formulation (time evolution) of interference patterns.*

Although it is well-known that the photon impact process is Poissonian (Mandel, 1958), the formulation process of interference pictures was not embedded into the standardized paradigm of probability theory up to now. On the ground of quantum-optical calculations and statistical analysis I proposed the vector-valued doubly stochastic Poisson process model.

THESIS 2. (Section 4.3). *I developed a new method for minimizing the output frequency fluctuations of semiconductor laser diodes.*

I proposed the application of semiconductor lasers for producing interference, instead of the usual gas or solid-state lasers. Laser diodes are well-known, can easily be configured in experimental environments and reasonably priced but the area of use is limited, mostly because of the instability of their frequency outcome. I suggested active frequency stabilization (in addition to passive one, see Ohtsu, 1992) for the semiconductor laser system in order to apply as a coherent source in the interferometric experiment.

THESIS 3. (Sections 5.1–3). *I set up an experimental layout for registering the time formulation of interference patterns.*

Although this seems to be a straightforward goal, nonetheless one have to face with both theoretical and practical difficulties. First of all, some measurement results should be collected. This is certainly not a trivial problem, Chapters 3 to 5 summarize the proposed experimental layout and describe the necessary equipment in technical terms. The experimental layout itself is a proposition as it became available only in the last few years to combine a high speed photodetector array with a high speed data acquisition card and record time statistics for the photonic arrival process.

THESIS 4. (Section 6.4). *I concluded in the optimal sampling time for statistical modelling of the photonic arrival process.*

Before system identification was performed I had to consider the "detectors' inefficiency" problem and the "sampling time selection" problem. These two are hopefully resolved by a new approach based on fractal theory. In Chapter 6 I introduced the concept of point fractals and proved that the photon arrival process is self-similar in a statistical sense (cf. Lovejoy et al., 1987). After investigating the existence of scale invariance I could draw up two statements: 1) the efficiency of detection does not effect substantially on the statistical properties of the photonic arrival process, and 2) for the photonic arrival process under investigation the return period is approximately 1ms.

THESIS 5. (Section 8.5). *I derived the optimal linear filtering algorithm for vector-valued doubly stochastic Poisson processes.*

As the final objective of research was the statistical identification for generating information processes of interference patterns, I should elaborate an optimal filtering algorithm for the embedded intensity process. Assuming linearity, the optimal filter is the Kalman–Bucy filter, and for vector-valued doubly stochastic Poisson processes it is formulated in the Multichannel Linear Filtration Theorem.

Interpretation and Application

Identification for underlying intensity processes resulted in fascinating issues: although the original counting processes are spatially separated, they can not be distinguished in a statistical sense, while the intensity processes have definitely different frequency characteristics.

The first observation is far from surprise, quantumoptics predicted the same outcome. However, separability of intensity processes is especially worth for thinking, and a parallelism can be drawn with the theory of Fine: it can be supposed that time evolution of the statistical sample contains some information related to the original abundance.

In my interpretation this is an evidence for the existence of some kind of global *hidden information pattern* that should correspond to Karl Popper's *third world*. I did not want to fell in the mistake of vanity and not take an attempt at explaining (or resolving) the Einstein–Podolsky–Rosen paradox that is in focus of interest of the scientific community for more than 65 years. Instead, in the last Chapter I pointed out some of the known absences of my model and outline the directions for further research.

The algorithm for frequency stabilization of laser diodes offers a far more practical application area. The introduction of this method into industrial framework is under research (Nádai, 2001).

References

Aspect, A., J. Dalibard, and G. Roger: 1982, 'Experimental test of Bell's inequalities using time-varying analyzers'. *Phys. Rev. Lett.* **49**(25), 1804.

Bell, J.: 1964, 'On the Einstein-Podolsky-Rosen paradox'. *Physics* **1**(3), 195.

Bohm, D.: 1952, 'A suggested interpretation of the quantum theory in terms of "hidden" variables: Part I'. *Phys. Rev.* **85**, 166–179.

Clauser, J., M. Horne, A. Shimony, and R. Holt: 1969. *Phys. Rev. Lett.* **23**, 880.

Fine, A.: 1982, 'Some local models for correlation experiments'. *Synthese* **50**, 279.

Lovejoy, S., D. Schertzer, and A. Tsonis: 1987. *Science* **235**, 1036.

Mandel, L.: 1958. *Proc. Phys. Soc.* **72**, 1037.

Ohtsu, M.: 1992, *Highly Coherent Semiconductor Lasers*. Norwood, MA: Artech House.

Popper, K. R.: 1972, *Objective Knowledge: An Evolutionary Approach*. Oxford: Clarendon Press. Revised ed. in 1983.

List of Publications

Joó, I., J. Bokor, V. P, and L. Nádai: 1996a, 'A new approximation method for transfer function estimation using its values in discrete points on the boundary of the unit circle'. Research report, Automation and Control Research Institute of the Hungarian Academy of Sciences, Budapest, Hungary.

Joó, I., L. Kóczy, and P. V. L. Nádai: 1997a, 'On control of non-smoothing systems'. In: P. Gabko (ed.): *Proc. Workshop AUTOMATION 2001*. Vienna, Austria, p. 285. (abstract).

Joó, I., L. Palkovics, P. Várlaki, and L. Nádai: 1997b, 'Identifibility of vibrating membranes and plates with restrained controls'. In: *Proc. 11th IFAC Symposium on System Identification*. Kitakyushu, Japan, pp. 153–158.

Joó, I., P. Várlaki, and L. Nádai: 1996c, 'Riesz bases in control theory (Controlling an oscillating string)'. In: P. Gabko (ed.): *Proc. Workshop on Advanced Control Systems*. Vienna, Austria, pp. 201–205.

Kóczy, L., P. Várlaki, and L. Nádai: 1998, 'Fuzzy system identification method for cognitive and decision processes'. In: *IEEE System, Man and Cybernetics*. San Diego, USA.

Kóczy, L. T., P. Várlaki, L. Kunsági, and L. Nádai: 1995, 'Fuzzy linguistic expert systems and models'. In: *Proc. Conference on Operation Research*. Balatonkenese, Hungary, pp. 26–27. (in Hungarian).

Nádai, L.: 1992, 'Effect of ultrashort light pulse on thin optical layer'. In: *Proc. Students' Conference at TUB*. Budapest, Hungary. (in Hungarian).

Nádai, L.: 1993, 'Effect of ultrashort light pulse on thin optical layer'. In: *Proc. Hungarian Students' Conference*. Kecskemét, Hungary, p. 180. (in Hungarian).

Nádai, L.: 1994a, 'Assuring Frequency Stability of Semiconductor Lasers by Control Methods'. Master's project, Technical University of Budapest, Department of Telecommunications and Telematics. (in Hungarian).

Nádai, L.: 1994b, 'Optimal frequency stabilization of semiconductor lasers'. Research report, Automation and Control Research Institute of the Hungarian Academy of Sciences, Budapest, Hungary. (in Hungarian).

Nádai, L.: 1995a, 'Photo-multipliers'. Research report, Dept. of Telecommunications and Telematics, Technical University of Budapest, Budapest, Hungary. (in Hungarian).

Nádai, L.: 1995b, 'Structure and parameter identification for the dynamic model of the integrated laser system establishing optimal control'. In: E. Halász (ed.): *Proc. Conference of Ph.D. Students*. Budapest, Hungary, pp. 39–40.

Nádai, L.: 1996a, 'An introduction to qualitative physics'. Technical report, LAAS–CNRF, Toulouse, France.

Nádai, L.: 1996b, 'An introduction to qualitative physics'. In: E. Halász (ed.): *Proc. Conference of Ph.D. Students*. Budapest, Hungary, pp. 31–32.

Nádai, L., Z. Papp, J. Bokor, and P. Várlaki: 1995a, 'On optimal frequency stabilization of semiconductor lasers'. In: J. Shinar (ed.): *Proc. 10th IFAC Workshop on Control Applications of Optimization*. Technion, Haifa, Israel.

Nádai, L., Z. Papp, and P. Várlaki: 1995b, 'Identification and control for optimal frequency stabilization of semiconductor lasers'. In: P. Gabko (ed.): *Proc. Workshop on Automation and Control Engineering in Higher Education*. Vienna, Austria.

Nádai, L.: 2001, 'Semiconductor Laser Applications'. *Contract between the author and FETI Ltd.*

Nádai, L.: 2002, 'Modelling photon counting experiments using fuzzy logic controller'. *Journal of Advanced Computational Intelligence*, Fuji Technology Press. (accepted for publication)

Michelberger, P., L. Nádai, P. Várlaki, I. Joó: 2002, 'Riesz bases in control theory'. *Periodica Polytechnica*, Budapest University of Technology and Economics. (accepted for publication)

Palkovics, L., I. Joó, P. Várlaki, and L. Nádai: 1996, 'On controllability of road vehicle vibrating membranes'. In: I. Zobory (ed.): *Proc. 5th Conference on Vehicle System Dynamics, Identification and Anomalies*. Budapest, Hungary.

Papp, Z. and L. Nádai: 1993, 'Numerical study of influence of ultrashort light pulse on thin optical layer'. In: *Topical Meeting 'Education and Training in Optics'*. Pécs, Hungary.

Papp, Z., P. Várlaki, and L. Nádai: 1997, 'Wave packet model and Mach–Zehnder type interferometers'. In: *Conference on Locality and Causality in Quantum Optics and Cosmology*. Toronto, Canada.

Papp, Z., P. Várlaki, and L. Nádai: 1998, 'Wave packet model and Mach–Zehnder type interferometers'. In: G. Hunter, S. Jeffers, and J.-P. Vigier (eds.): *Causality and Locality in Modern Physics*, Fundamental Theories of Physics. The Netherlands: Kluwer Academic Publishers, pp. 373–382.

Penninger, A., L. Kóczy, P. Várlaki, and L. Nádai: 1998, 'Stochastic and fuzzy decision models in energetics'. In: *3rd World Automation Congress*. Anchorage, USA.

Várlaki, P. and L. Nádai: 1995, 'Expert investment decision models using subjective learning algorithms'. In: N. Kasabov (ed.): *Proc. 2nd International Two-Stream Conference on Artificial Neural Networks and Expert Systems (ANNES '95)*. Dunedin, New Zealand.

Várlaki, P. and L. Nádai: 1996, 'Qualitative modelling of vehicle vibrating structures'. In: L. T. Kóczy (ed.): *Proc. Symposium on Qualitative System Modelling, Qualitative Fault Diagnosis and Fuzzy Logic and Control*. Budapest, Hungary.

Várlaki, P., L. Palkovics, and L. Nádai: 1997a, 'System identification of vibrating membranes with restrained control'. In: P. Gabko (ed.): *Proc. Workshop AUTOMATION 2001*. Vienna, Austria, pp. 217–224.

Várlaki, P., Z. Papp, L. Nádai, and I. Joó: 1998a, 'Stochastic control model for H-atoms (Non-radiating solution of the classical Bohr model)'. In: *3rd APCCM*. Tunhuang, China.

Várlaki, P., Z. Papp, L. Szeidl, and L. Nádai: 1998b, 'Probabilistic models for measures of dependence in quantumoptical measurements'. In: *3rd World Automation Congress*. Anchorage, USA.

Várlaki, P., L. Szeidl, and L. Nádai: 1997b, 'A new approach for calculating the measures of dependence for interference statistics'. In: *Proc. DIMACS Workshop on Statistical Physics Methods in Discrete Probability, Combinatorics and Theoretical Computer Science*. Princeton, NJ.

Várlaki, P., L. Szeidl, and L. Nádai: 1997c, 'New stochastic approach for measuring and controlling photon statistics'. In: P. Gabko (ed.): *Proc. Workshop AUTOMATION 2001*. Vienna, Austria, pp. 253–256.

Várlaki, P., G. Terdik, and L. Nádai: 1995, 'On problem of stochastic bilinear realization'. In: C. Kwong (ed.): *Mini Symposium at the Chinese University of Hong Kong*. Shatin, NT, Hong Kong.