Diplomarbeit

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Bibliographic information published by the German National Library:

The German National Library lists this publication in the National Bibliography; detailed bibliographic data are available on the Internet at http://dnb.dnb.de .

ISBN: 9783836644396

http://www.diplom.de/e-book/227686/optical-and-electrical-properties-of-single-self-assembled-quantum-dots

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ISBN: 978-3-8366-4439-6
Herstellung: Diplomica® Verlag GmbH, Hamburg, 2010
Zugl. Technische Universität München, München, Deutschland, Diplomarbeit, 2009

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Das Wetter war stürmisch; der Himmel dicht bewölkt; die Dunkelheit … undurchdringlich … Durch ein solches Laublabyrinth, und in völliger Finsternis, mußten die Falter sich einen Weg suchen, um ans Ziel ihrer Wallfahrt zu gelangen.

Kein Käuzchen würde es unter diesen Umständen wagen, die Höhlung seines Ölbaums zu verlassen. Der Schmetterling … zieht ohne Zögern seine Bahn … So geschickt lenkt er seinen verschlungenen Flug, dass er, allen Hindernissen zum Trotz, in einem Zustand vollkommerner Frische anlangt, die großen Schwingen ganz unversehrt … Die Dunkelheit ist Licht genug …

J. H. Fabre

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When I hear of Schrödinger's cat,
I reach for my gun.

Stephen Hawking

CHAPTER 1

Motivation: Entangled Photons

In this thesis we investigate the optical properties of self-assembled quantum dots exposed to a lateral electric field. As a result of the electric field the wave functions of electrons and holes inside the quantum dot are manipulated, which makes it possible to tune their energy levels and control the optical properties of the system. The possibility of tuning the emission energy of different few particle states using this method makes this system very promising for the use of a source of polarization entangled photons as discussed in the following sections.

In Section 1.1 the concept of entangled states is introduced together with a brief historical overview. The possibility of using the exciton–biexciton cascade of a self-assembled quantum dot for the generation of entangled photon pairs is presented in Section 1.2.

1.1 Entangled States

The concept of *entanglement* deemed to be one of the most fascinating and impressive phenomena in modern quantum physics. Parts of it are well-known far beyond the borders of the physics world, for example discussions about the state of health of Schrödinger's cat [Sch35] are not only led by physicists.

The history of entanglement began in 1935 when two pioneering papers were published. First, Einstein, Podolsky and Rosen wrote their famous "EPR" paper raising the question: *"Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"* [Ein35] The paper discusses the properties of an entangled two-particle system formed from a radioactive decay. Soon afterward, Schrödinger published the paper on his famous cat paradox, where the word entanglement (German: "Verschränkung") was mentioned for the first time to describe the physical properties, as explained in the following [Sch35].

We introduce the concept of entanglement on the basis of a quantum correlated photon pair. As polarization basis we chose horizontal and vertical polarization and designate the polarization states $|\updownarrow\rangle$ and $|\leftrightarrow\rangle$. These polarizations can experimentally be determined by using a polarization filter orientated in the right direction (horizontal or vertical) followed by a single-photon detector.

A basic requirement to achieve entanglement is a photon source that generates *correlated photon pairs*. Such photon pairs have the following properties:

1. The polarization of either photon 1 or photon 2 measured independently of the other is random. That means by just looking at for example photon 1, the probabilities of measuring the polarizations $|\updownarrow\rangle$ and $|\leftrightarrow\rangle$ are the same and equal to $\frac{1}{2}$.

2. The polarizations of the photon pair are perfectly correlated. That means in the case of positive correlation that for both photons the polarization is either $|\updownarrow\rangle$ or $|\leftrightarrow\rangle$. In the case of negative correlation, the polarization of one of the photons is $|\updownarrow\rangle$ while the polarization of the other one has to be $|\leftrightarrow\rangle$.

The two particles are said to be in an entangled state if their wave function cannot be factorized into a product of the two individual particles. For the correlated photon pair, the wave function in the case of perfect positive correlation has to be written in the form:

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}} \left(|\updownarrow_1, \updownarrow_2\rangle \pm |\leftrightarrow_1, \leftrightarrow_2\rangle \right) \tag{1.1}$$

and in the case of perfect negative correlation it has to be written in the form:

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}} \left(|\updownarrow_1, \leftrightarrow_2\rangle \pm |\leftrightarrow_1, \updownarrow_2\rangle \right) . \tag{1.2}$$

The subscripts 1 and 2 refer to the individual photons.

Consequently, entanglement leads to the fact that the quantum states (in this case the polarization) of the two photons no longer can be regarded as being independent from each other. Their quantum states are said to be *entangled*. The measurement of the polarization of photon 1 simultaneously determines the polarization of photon 2, even if the system is spatially separated.

This behavior appears surprising because at first glance, it seems to violate the rule that no information can be transmitted faster than the speed of light. In fact, this *no communication theorem* [Per04] is not violated since no information can be transmitted with a measurement like this. As defined by the first condition for correlated photon pairs, the measurement of either $|\updownarrow\rangle$ or $|\leftrightarrow\rangle$ can not be enforced and has to be random, which makes it impossible to generate information and process it with such an EPR pair.

The "EPR paradox" as this phenomenon is often referred to, immediately raises another question: Does the polarization measurement of the first photon really determine the polarization of the second one, or is there a *hidden variable* that determines the polarizations of the particles from the beginning on? To answer that question, John Bell set up an equation in 1946, which is referred to as *Bell's inequality* [Bel64]. The violation of this inequality would prove the absence of hidden variables and support the quantum mechanical point of view as explained above. Actually, three experiments could prove the violation of Bell's inequality between 1981 and 1982 [Asp81, Asp82b, Asp82a]. These experiments were a fundamental step toward modern quantum theory, since they