Supervisor's Foreword

"*What is light?*" is a question which has fascinated humanity certainly since the earliest dates of written documents. But it is a fair guess that even the first humans, looking up at the night sky, wondered about the nature of light. Consequently, the study of the nature of light has accompanied the development of science in general and of physics in particular over all of its history. In the 20th century, light became *the* paradigmatic example in the debates on the conceptual challenges raised by the then new quantum mechanics. Einstein, as early as in 1905, when he proposed the existence of particles of light, realized the tension with the then prevalent wave picture. Many gedanken experiments, often using individual photons, the particles of light, served to underline the counterintuitive predictions of quantum physics for individual quanta. Real experiments were not possible in the 1920s and 1930s due to the rather limited technology at that time.

Technical progress, most importantly the invention of the laser, made experiments with individual photons possible. To date, numerous experiments have confirmed the dual wave and particle nature of light. Consequently, work with single photons is established routine in many laboratories around the world and has even entered student laboratory courses.

In his work, Robert Fickler combines two conceptually interesting features of light in novel and ingenious ways. On the one hand, there is entanglement, which is the correlation between distant measurement results without any possibility of a classical realistic explanation. Einstein called this phenomenon "spooky action at a distance" and he was hoping for a quantum physics without such counterintuitive features. On the other hand, there is the novel feature of orbital angular momentum of light, which only came to the attention of the scientific community in the 1990s. The notion of orbital angular momentum carries the possibility that a single photon can carry in principle any amount of angular momentum. In quantum language, in can possess arbitrarily high quantum numbers. The related possibility of the transverse modulation of a light wave, allows novel polarization amplitude and phase patterns to be imprinted on the light beam, even at the single photon level.

It is often said that a transition from quantum to classical phenomena occurs for high quantum numbers. Thus, the potential of a photon to carry arbitrarily large quantum numbers leads, in the eyes of some, to the possibility of studying in detail the quantum to classical transition. In one of his experiments, Robert Fickler demonstrated the entanglement of two photons, each one carrying either $+300\,\hbar$ or $-300\,\hbar$ units of orbital angular momentum. In simple language, this means that neither photon carries any angular momentum until one of them is measured. Then the other one is instantly collapsed into the opposite state. This is certainly the highest number of quanta ever entangled in any experiment. In other words, there is no indication for a transition to classical behavior for these quantum numbers.

To further underline the interesting notion of entanglement, in another experiment Robert Fickler was able to show on a single-photon camera directly in a live movie the change of an orbital angular momentum quantum state of one photon and its dependence on the kind of measurement performed on the other one. This experiment provides a very clear demonstration of the counterintuitive features of quantum entanglement.

Finally, exploiting the possibility of arbitrary transverse modulation of a light beam, Fickler demonstrated the novel, very complex polarization vector and amplitude modulation patterns and their entanglement, again for individual photons. A rather curious result is that two vector photons can be both entangled and not entangled at the same time, depending on the specific measurement performed on them.

Robert Fickler's thesis also opens avenues to novel applications for quantum communication with photons. Particularly the possibility that an individual photon can carry very high quantum numbers allows breaking the barrier that a single photon carries only one bit of information or one qubit of quantum information. Furthermore, his results allow novel quantum cryptography protocols with additional security features.

It is thus evident that Robert Fickler's thesis breaks very new ground in the age-old study of the nature of light and its applications.

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