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DISCUSSION

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A comment on the paper by R.I. Khrapko 'On the possibility of an experiment on 'nonlocality' of electrodynamics'

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Abstract. **This methodological note is dedicated to the analysis of the imaginary experiment proposed by R.I. Khrapko in the paper 'On the possibility of an experiment on 'nonlocality' of electrodynamics' [*Quantum Electronics*, 42, 1133 (2012)].**

Keywords: *manipulation of macroscopic particles, angular momentum, Beth effect, Righi effect.*

Beth's experiment [1] was one of the key experiments to justify the quantum-mechanical views on optical radiation. The essence of this experiment was to demonstrate that a change in the spin of a light quantum during its interaction with matter is accompanied by the angular momentum transfer to matter. For example, during the passage of the circularly polarised light through a half-wave plate, the state of light polarisation is reversed. This means that each photon spin changes its sign, and the plate acquires an angular momentum that is proportional to the number of quanta passed through the plate. It is of interest to note that, at one and the same energy of a radiation pulse, this effect is the stronger the greater is the wavelength of light. This effect is very weak – it suffices to note that its observation requires neutralisation of a much greater effect of light pressure. Nevertheless, Beth was able to observe it. He used a torsional pendulum, the rotating mass of which was formed by a half-wave plate. The influence of light pressure was zeroed due to the double passage of light through the plate in both directions. Beth was able to detect a change in the parameters of torsional oscillations and to perform quantitative evaluations of the effect. This classic experiment not only confirmed the rotational nature of spin, but also allowed the Planck constant to be for the first time estimated quantitatively (in other words, to be measured).

Later, this experiment was multiply repeated (see, for example, [2, 3]). The use of a continuous-wave CO_2 laser [2] made it possible to obtain an immediate 'twisting' of the torsion pendulum, while the use of microwave radiation [3] makes the effect quite 'tangible'.

Today, the use of this effect for manipulation by small, but still macroscopic particles is of special interest. In this connection, it is of importance to describe this effect within the framework of classical macroscopic physics, i.e. in the case under consideration – in the language of ordinary electrodynamics. To our knowledge, a comprehensive theory of this effect, with allowance for the propagation of radiation through a birefringent medium, has not been constructed yet, but, as was shown in a number of studies (see, for example, [4, 5]), the electromagnetic field of light should possess a nonzero component in the direction of light wave propagation to make possible the angular momentum transfer possible. Such a non-zero component arises in the beams with phase and (or) intensity being non-constant along the cross section, i.e. in all cases except an ideal plane wave. In this case, the attempts of analysis lead to the 'plane wave paradox'. Currently, the majority of authors (see, for example, the same works [4, 5]) suggest that this paradox is a seeming one – a plane wave represents an idealisation, while in the real experiment all beams and elements have a finite aperture, and diffraction on that aperture provides the required longitudinal component of the electromagnetic field of the light wave.

However, the authors of [6] tries to find another solution to this paradox, which assumes a nonlocal character of the electromagnetic field. In particular, he has proposed previously [7] an imaginary experiment on observation of the Beth effect in a concentric composite absorbing plate, assuming that the inner plate having no fringe effects in its aperture will nevertheless rotate due to the external field action. This imaginary experiment is analysed in detail in paper [8], where it is shown that fanciful 'non-locality' of Maxwell's equations is not observed in this case, the correspondence principle in transition from quantum to classical description is fulfilled, and each of the plates will be rotating in strict dependence on the incident flow of photons and the angular momentum those photons transfer. From a formal viewpoint, the intensity gradient that arises at the boundary interface of the concentric half-wave plates is responsible for the phenomenon described.

In [6], the author offers an analogous imaginary experiment, in which, instead of the concentric absorbing plate, a similar half-wave phase plate should be used. It is obvious that, in the implementation of Beth's experiment in this case, the results of corresponding imaginary experiment would be the same, and the conclusions of [8] are fully valid in this case.

Further, the author [6] makes a serious methodological mistake in trying to perform an imaginary experiment in accordance with the Righi scheme using the same composite half-wave plate. In the Righi classic experiment [9, 10], a two-beam Mach–Zehnder interferometer is used, in each of the arms of which a half-wave plate is installed. A circularly polarised wave, which is fed to the interferometer, changes its polarisation direction to the opposite in the plates, and two-

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beam interference is observed at the interferometer output. Righi noticed that when one of the plates is rotated around the optical axis of the interferometer, the interference pattern fringes begin to 'move', and after a full turn of the plate the fringes are 'shifted' by two periods.

In quantum (microscopic) language, the Righi effect is explained similarly to the Beth effect: while passing through the plate, photons exchange their angular momentum with matter and thus change the initial value of spin to the opposite. Accordingly, the authors [6] has assumed that in this case the manifestations of a hypothetical 'non-locality' of the electromagnetic field are also possible, which, in his opinion, should lead to 'a large shift of the fringes on the edge of the illuminated area when the outer part of the plate is rotated' [6] (in the sense – greater than two periods of the shift of the interference fringes for a complete revolution of the plate – *annotated by the author*).

A mistake of the author [6] is that he has not taken into account a fundamental difference in interpretation of the Beth and Righi experiments in the macroscopic (classical) approximation. Even if such an interpretation of Beth's experiment does face the aforementioned difficulties leading to the 'plane wave paradox', the macroscopic interpretation of the Righi experiment is completely transparent and does not lead to any paradoxes, which can be seen from the following.

For simplicity, we refrain from mathematical description and consider a simplest imaginary experiment. Assume that at the initial time moment both of the two half-wave plates in the Righi experiment are in the same position – for example, the crystal axes of both of the birefringent plates are directed vertically. Let the lengths of the interferometer arms be the same. In this case, the waves at the interferometer output coincide in phase, the constructive interference occurs, and the total intensity of the wave is maximal. A circularly polarised wave at the interferometer input can be represented as a superposition of the vertical and horizontal linearly polarised waves, and both pairs of the linearly polarised waves in the above-described scheme interfere constructively.

Now suppose that one of the half-wave plates has been rotated by 90° around the optical axis of the interferometer. In this case, the phase incursion for the vertically polarised wave would be changed by $\lambda/2$ compared to the initial position of the plate, and the vertically polarised waves at the interferometer output would interfere destructively (up to the manufacturing error of the plate). The same would happen with the horizontally polarised wave, and, as a result, the total intensity of the circularly polarised waves at the interferometer output would also be minimal.

A rotation of the plate by yet another quarter of revolution would lead to the restoration of original picture (again, within the assumption on the plate's planarity) and so on. It is quite obvious that these arguments are valid both for an ideal plane wave and diverging waves considered in [6]. A trivial result of the imaginary experiment proposed in [6] is predictable: the fringes would 'run' within the aperture of the beam corresponding to the rotated plate, while the fringes in the rest part of the beam would remain quiescent.

The probable cause of erroneous predictions of the author [6] is another widespread methodological error, namely the attempt to interpret the non-stationary interference pattern of two light beams in terms of the 'displacement' of interference fringes. In some cases, in particular, when, in a stationary scheme, the interference pattern is of sophisticated nature, such an interpretation may lead to errors. To avoid this, it is advisable to use the concept of a time-dependent intensity in the interference pattern under study. In the Righi experiment, at each point of the output field that corresponds to the rotating half-wave plate, the interference field intensity undergoes a double full oscillation cycle and returns to its original value with a complete turn of the plate.

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