What is the spin proportional to?

Is spin density of light proportional to energy density or to gradient of the energy density?

This is a discussion. The discussion involves an exchange of opinions and three papers: the new paper, the first paper and another paper

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Dielectric absorbs spin of an infinite plane wave[1]

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It is demonstrated that a dielectric, which absorbs a circularly polarized perfect plane electromagnetic wave, absorbs spin. This means that the wave carries spin. And this fact is in accordance with the concept of the canonical spin tensor. The given calculations show that spin is the same natural property of a perfect plane electromagnetic wave, as energy and momentum, contrary to the standard opinion.

Key Words: classical spin; circular polarization; spin tensor
PACS 75.10.Hk

1. Introduction 1. Spin density is proportional to energy density

It was suggested as early as 1899 by Sadowsky [1] and as 1909 by Poynting [2], that any circularly polarized light carries angular momentum volume *density,* which is proportional to the energy volume density. That is the angular momentum is present in any point of the light.

> **J.H. Poynting:** If we put E for the energy in unit volume and G for the torque per unit area, we have $G = E\lambda/2\pi$ [2].

This sentence points that any absorption of a circularly polarized light results in a mechanical torque density acting on the absorber. We researched this effect and found that this torque density induces specific mechanical stresses in the absorber [3].

According to the Lagrange formalism, this angular momentum volume density is *spin density*. The spin of electromagnetic waves is described by a spin tensor [4 – 6].

$$\Upsilon^{\lambda\mu\nu} = -2A^{[\lambda}\delta^{\mu]}_{\alpha}\frac{\partial\mathcal{L}}{\partial(\partial_\nu A_\alpha)}, \qquad (1.1)$$

where $\mathcal{L}$ is a Lagrangian and A^λ is the magnetic vector potential of the electromagnetic field. So, any infinitesimal 3-volume dV_ν contains spin

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$$dS^{\lambda\mu} = \Upsilon^{\lambda\mu\nu} dV_{\nu} . \tag{1.2}$$

In particular, the canonical spin tensor are obtained by the Lagrange formalism from the canonical Lagrangian $\mathcal{L} = -F_{\mu\nu}F^{\mu\nu}/4$:

$$\Upsilon^{\lambda\mu\nu} = -2A^{[\lambda}F^{\mu]\nu} ; \tag{1.3}$$

here $F_{\mu\lambda}$ is the electromagnetic field tensor, and A^{λ} is the magnetic vector potential.

In the case of a *perfect* plane monochromatic circularly polarized electromagnetic wave travelling in z-direction and with infinite extension in the xy-directions

$$\breve{\mathbf{E}}_1 = E_1(\mathbf{x} + i\mathbf{y})\exp(ikz - i\omega t) \text{ [V/m]}, \quad \breve{\mathbf{H}}_1 = -i\varepsilon_0 c \breve{\mathbf{E}}_1 \text{ [A/m]}, \quad ck = \omega , \tag{1.4}$$

the component

$$\Upsilon^{xyz} = -2A^{[x}F^{y]z} = A_x H_x + A_y H_y \text{ [J/m}^2\text{]} \tag{1.5}$$

of the spin tensor (1.3) gives the spin flux density directed along z-axis.

The spin tensor (1.3) was successfully used in order to confirm the fulfillment of the conservation laws with respect to flux densities of momentum, energy, spin, and number of photons when a plane circularly polarized electromagnetic wave with infinite extension reflects from a receding mirror [7]. These calculations prove the functionality of the spin tensor and show that spin is the same natural property of a perfect plane electromagnetic wave, as energy and momentum, and spin density is proportional to energy density.

The classical experiments [8 – 11] confirm that the spin density of plane waves is proportional to energy density. In these experiments, the angular momentum of the light was transferred to a half-wave plate, which rotated. So work was performed in any point of the plate. This (positive or negative) amount of work reappeared as an alteration in the energy of the photons, i.e., in the frequency of the light, which resulted in moving fringes in any suitable interference experiment.

Some texbooks point that infinite plane circularly polarized electromagnetic wave carries angular momentum:

> **F.S. Crawford, Jr.**: "A circularly polarized travelling plane wave carries angular momentum" [12, p. 365].
> **R. Feynman**: "… the photons of light that are right circularly polarized carry an angular momentum of one unit along the z-axis …light which is right circularly polarized carries an energy and angular momentum" [13].

2. Introduction 2. Is the spin density proportional to gradient of the energy density?

However, since 1939, another concept of electrodynamics spin is in use. The point is, Belinfante & Rosenfeld added specific terms,

$$\partial_{\alpha}(A^{\mu}F^{\nu\alpha}) \text{ and } 2\partial_{\alpha}(x^{[\lambda}A^{\mu]}F^{\nu\alpha}) , \tag{2.1}$$

to the canonical energy-momentum and total angular momentum tensors (2.2) and (2.3) respectively [14,15]

$$\underset{c}{T}^{\mu\nu} = -\partial^{\mu}A_{\alpha}F^{\nu\alpha} + g^{\mu\nu}F_{\alpha\beta}F^{\alpha\beta}/4 \tag{2.2}$$

$$\underset{c}{J}^{\lambda\mu\nu} = 2x^{[\lambda}\underset{c}{T}^{\mu]\nu} + \underset{c}{\Upsilon}^{\lambda\mu\nu} = 2x^{[\lambda}\underset{c}{T}^{\mu]\nu} - 2A^{[\lambda}F^{\mu]\nu} . \tag{2.3}$$

This procedure gives the energy-momentum tensor, $\underset{st}{T}^{\mu\nu}$, and the total angular momentum tensor $\underset{st}{J}^{\lambda\mu\nu}$, which we named "standard" [3].

$$\underset{st}{T}^{\mu\nu} = \underset{c}{T}^{\mu\nu} + \partial_{\alpha}(A^{\mu}F^{\nu\alpha}) , \tag{2.4}$$

$$\underset{st}{J}^{\lambda\mu\nu} = 2x^{[\lambda}\underset{c}{T}^{\mu]\nu} - 2A^{[\lambda}F^{\mu]\nu} + 2\partial_{\alpha}(x^{[\lambda}A^{\mu]}F^{\nu\alpha})$$

$$= 2x^{[\lambda}\underset{c}{T}^{\mu]\nu} - 2A^{[\lambda}F^{\mu]\nu} + 2\delta^{[\lambda}_{\alpha}A^{\mu]}F^{\nu\alpha} + 2x^{[\lambda}\partial_{\alpha}(A^{\mu]}F^{\nu\alpha}) = 2x^{[\lambda}\underset{st}{T}^{\mu]\nu} . \tag{2.5}$$

But this procedure eliminates spin tensor ($\underset{\text{st}}{\Upsilon}^{\lambda\mu\nu} = 0$) because the standard total angular momentum tensor (2.5) equals moment of the corresponding energy-momentum tensor only. As a result, in the absence of electrodynamics spin tensor, it was declared the absence of spin in a plane wave, and the electrodynamics spin was defined as a part of a moment of linear momentum [16, p. 7].

$$\mathbf{J} = \int dV\varepsilon_0 \mathbf{r}\times(\mathbf{E}\times\mathbf{B}) = \mathbf{L} + \mathbf{S}\,.$$

> **Heitler W:** "A plane wave travelling in z-direction and with infinite extension in the xy-directions can have no angular momentum about the z-axis, because $(\mathbf{E}\times\mathbf{B})$ is in the z-direction and $(\mathbf{r}\times(\mathbf{E}\times\mathbf{B}))_z = 0$" [17]

According to the nowday conception, electrodynamics spin density is proroptional to *gradient of energy density*

> **Allen L., Padgett M. J.:** "… the local spin angular momentum density per photon is proportional to the radial intensity gradient of a light beam:
>
> $$j_z = -\frac{r}{2u^2}\frac{\partial(u^2)}{\partial r}\hbar\sigma$$
>
> where $\sigma = \pm 1$ for right- and left-handed circularly polarized light respectively, u^2 is the beam intensity, and *r* is the distance from the axis. For a plane wave there is no gradient and the spin density is zero." [18]
>
> **Simmonds J. W., Guttmann M. J.:** "The electric and magnetic fields can have a nonzero z-component only within the skin region of this wave. Having z-components within this region implies the possibility of a nonzero z-component of angular momentum within this region. So, the skin region is the only in which the z-component of angular momentum does not vanish" [19, p. 227]

We have noted [20] that this concept "Spin is only in the skin region" threatens us with a considerable nonlocality of the electrodynamics because the concept implies that energy and momentum of photons are absorbed everywhere in the absorber, but spin is absorbed in the remote boundary of the wave.

In this paper, we confirm the Poynting's and Sadowsky's concept by a new calculation. We consider absorption of spin, momentum and energy of an infinite wave by a dielectric.

3. The Poynting vector Π

Let a plane monochromatic circularly polarized electromagnetic wave (1.4)

$$\mathbf{E}_1 = E_1(\mathbf{x} + i\mathbf{y})\exp(ikz - i\omega t)\ \text{[V/m]},\quad \mathbf{H}_1 = -i\varepsilon_0 c\mathbf{E}_1\ \text{[A/m]},\quad ck = \omega \tag{3.1}$$

impinges normally on a flat surface of lossy dielectric, which is characterized by a complex permittivity $\breve{\varepsilon}$ (we mark complex numbers and vectors by *breve*). As is known, in this case, the reflected and the passed waves have the forms

$$\breve{\mathbf{E}}_2 = \breve{E}_2(\mathbf{x} + i\mathbf{y})\exp(-ikz - i\omega t)\,,\quad \breve{\mathbf{H}}_2 = i\varepsilon_0 c\breve{\mathbf{E}}_2\quad \breve{E}_2 = \frac{1-\breve{k}}{1+\breve{k}}E_1\quad \breve{k} = \sqrt{\breve{\varepsilon}} = k' + ik'' \tag{3.2}$$

$$\breve{\mathbf{E}}_3 = \breve{E}_3(\mathbf{x} + i\mathbf{y})\exp(ik\breve{k}z - i\omega t)\,,\quad \breve{\mathbf{H}}_3 = -i\varepsilon_0 c\breve{k}\breve{\mathbf{E}}_3\,,\quad \breve{E}_3 = \frac{2}{1+\breve{k}}E_1 \tag{3.3}$$

($\breve{k}$ designates the complex refraction coefficient).

The mass-energy flux density, which impinges normally on the dielectric surface and then is absorbed by the dielectric, i.e. the total Poynting vector Π, can be calculated taking into account that the incident and reflected beams do not interfered with each other, and, so, one may simply subtract energy flux density of the reflected beam from energy flux density of the incident beam.

$$\Pi = \Pi_1 - \Pi_2 = \varepsilon_0 cE_1^2 - \varepsilon_0 c\left|\breve{E}_2\right|^2 = \varepsilon_0 cE_1^2\left(1 - \left|\frac{1-\breve{k}}{1+\breve{k}}\right|^2\right) = \varepsilon_0 cE_1^2\frac{4k'}{(1+k')^2 + k''^2}\ \left[\frac{\text{J}}{\text{m}^2\text{s}}\right]. \tag{3.4}$$

4. The absorption of energy and angular momentum by the dielectric

The energy flux density (3.4) enters into the dielectric and can be calculated by the use of expression (3.3) for the wave inside the dielectric. A mechanism of the absorption such a wave was explained by Feynman [13]: the rotating electric field $\breve{\mathbf{E}}_3 = \breve{E}_3(\mathbf{x}+i\mathbf{y})\exp(-i\omega t)$ exerts a torque $\tau = \breve{\mathbf{d}}\times\breve{\mathbf{E}}_3$ on rotating dipole moments of molecules $\mathbf{d}$ of the polarized dielectric and makes a work. The power volume density of this work has the form

$$w = \left|\breve{\mathbf{P}}\times\breve{\mathbf{E}}_3\right|\omega \ \ [\text{W/m}^3], \quad \breve{\mathbf{P}} = (\breve{\varepsilon}-1)\varepsilon_0\breve{\mathbf{E}}_3, \quad \breve{\varepsilon} = \breve{k}^2 = k'^2 - k''^2 + 2ik'k'', \tag{4.1}$$

$\breve{\mathbf{P}}$ is the polarization vector, and $\breve{\mathbf{P}}\times\breve{\mathbf{E}}_3$ [J/m^3] is a *torque volume density*[3]. The calculation gives

$$w = \frac{\omega}{2}\Re\{\breve{P}_x\overline{E}_{3y} - \breve{P}_y\overline{E}_{3x}\} = \frac{\omega\varepsilon_0}{2}\Re\{(\breve{\varepsilon}-1)(\breve{E}_{3x}\overline{E}_{3y} - \breve{E}_{3y}\overline{E}_{3x})\} = \frac{\omega\varepsilon_0}{2}\exp(-2kk''z)\Re\{(\breve{\varepsilon}-1)(-i-i)\}\left|\breve{E}_3\right|^2$$
$$= \omega\varepsilon_0\exp(-2kk''z)\Im(\breve{\varepsilon}-1)\left|\breve{E}_3\right|^2 = \omega\varepsilon_0\exp(-2kk''z)2k'k''\left|\breve{E}_3\right|^2. \tag{4.2}$$

The energy flux density, which comes on the surface of dielectric from the waves, can be obtained by an integration of the power volume density (4.2) over z

$$\Pi = \int_0^\infty w\,dz = \omega\varepsilon_0\int_0^\infty \exp(-2kk''z)2k'k''\left|\breve{E}_3\right|^2 dz = \omega\varepsilon_0\frac{k'}{k}\left|\breve{E}_3\right|^2 = \varepsilon_0 c E_1^2\frac{4k'}{(1+k')^2+k''^2}. \tag{4.3}$$

This expression is coincident with (3.4).

But we must recognize that the torque volume density[4] $\tau_{\sim} = \breve{\mathbf{P}}\times\breve{\mathbf{E}}_3$, which supply with energy the interior of the dielectric, in the same time, is a volume density of angular momentum flux, which comes inside the dielectric. The torque volume density $\breve{\mathbf{P}}\times\breve{\mathbf{E}}_3$ produces specific mechanical stresses in the dielectric [3]. And, as the volume density of angular momentum flux, the torque volume density requires angular momentum flux density, which comes on the dielectric surface from the waves. We get this angular momentum flux density by integrating the torque volume density $\tau_{\sim}$ over z.

$$\Upsilon = \int_0^\infty \left|\breve{\mathbf{P}}\times\breve{\mathbf{E}}_3\right| dz = \frac{1}{\omega}\int_0^\infty w\,dz = \frac{\Pi}{\omega} = \frac{\varepsilon_0 c E_1^2}{\omega}\frac{4k'}{(1+k')^2+k''^2} \quad \left[\frac{\text{J}}{\text{m}^2}\right]. \tag{4.4}$$

The results of this Section were first published in paper [21].

Now our task is to make sure that electromagnetic waves (3.1), (3.2) contain angular momentum flux density (4.4).

4. Calculation of an angular momentum flux density, which is contained in the electromagnetic waves

Because angular momentum (4.4) is absorbed under every square meter of the dielectric surface per second, one can conclude that the angular momentum is brought to the surface by waves (3.1), (3.2). To calculate this bringing angular momentum flux, it is natural to use the equation (1.5) for the spin flux density

$$\Upsilon^{xyz} = -2A^{[x}F^{y]z} = A_x H_x + A_y H_y \ \ [\text{J/m}^2]. \tag{5.1}$$

Note that the lowering of the spatial index of the vector potential is related to the change of the sign in the view of the metric signature $(+---)$. Since for a monochromatic field $A_k = -\int E_k dt = -iE_k/\omega$, densitiy (5.1) can be expressed through the electromagnetic field:

$$\Upsilon^{xyz} = (-iE_x H_x - iE_y H_y)/\omega. \tag{5.2}$$

In our case, we have for the incident and reflected waves, similarly to (3.4)

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[3] Do you remember? Poynting's G is a torque surface density!

[4] We mark pseudo densities by index *tilda*. The volume density of moment of force $\tau_{\sim}$ .is a pseudo density, as opposed to the moment of force τ.

$$\Upsilon^{xyz} = \Re\{-iE_{1x}\overline{H}_{1x} - iE_{1y}\overline{H}_{1y} - i\breve{E}_{2x}\overline{H}_{2x} - i\breve{E}_{2y}\overline{H}_{2y}\}/2\omega$$
$$= \frac{\varepsilon_0 c}{\omega}\left(E_1^2 - \left|\breve{E}_2\right|^2\right) = \frac{\varepsilon_0 c E_1^2}{\omega}\frac{4k'}{(1+k')^2 + k''^2}. \quad (5.3)$$

Expressions (4.4) and (5.3) coincide. Expressions (3.4) and (5.3) differ by the factor ω. This result was also presented in paper [21]. The observable equality $\Upsilon = \Pi/\omega$ is a consequence of the relation between photon spin $\hbar$ and photon energy $\hbar\omega$.

5. Conclusion

The given calculations show that spin is the same natural property of an infinite plane electromagnetic wave, as energy and momentum. Recognizing the existence of photons with momentum, energy and spin in an infinite plane electromagnetic wave, it is strange to deny the existence of spin in such a wave, as is done in modern electrodynamics.

I am eternally grateful to Professor Robert Romer, having courageously published my question: "Does a plane wave really not carry spin?” [22]

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Journal of Modern Optics

In view of the criticisms of the reviewer found in the attachment, your manuscript # TMOP-2017-0226.R1 has been denied publication.

Dr Thomas Brown Editor in Chief

Referee report on the paper **"Absorption of angular momentum of a plane electromagnetic wave"** by Radi I. Khrapko

The refereed paper presents a theoretical analysis of the problem of absorption of a circularly polarized plane wave by a moving medium. I did not check the paper's calculations but have no ground to question their correctness. The problem itself is, maybe, of a certain scientific interest but the author does not explain the necessity and the meaning of his analysis. Granted that everything is correct, the question remains about the aim of this calculation. Is it so important to show that the equation for absorption of the field angular momentum (6.8) is quite similar to the equation describing the absorption of energy (4.2)?

The author claims that due to his calculations "we have to admit the existence of the spin density in the wave. The nowday widespread opinion has to be revised in view of the critisism" But I believe the author's reproaches to the physics community for denying the spin density in a circularly polarized plane wave are wrong. In fact, what the author stands for is a commonly shared opinion that nobody calls in question.

See, for example, F.S. Crawford, Jr., Waves: Berkley Physics Course - V. 3, Education Development Center, Inc., 1968, p. 365: ".. .A circularly polarized travelling plane wave carries angular momentum". The notion of the spin density of a plane wave is widely used in the current researches - e.g, K. Y. Bliokh, A. Y. Bekshaev, and F. Nori, "Extraordinary momentum and spin in evanescent waves", *Nature Commun.* **5,** 3300 (2014).

The list of authoritative and credible books, articles, etc., treating and using the spin density of a plane wave can be very long. However, the author cites some well known sources that express, apparently, the quite opposite statement: "A plane wave travelling in z-direction and with infinite extension in the xy-directions can have no angular momentum about the z-axis", and makes hence a conclusion that modern physics mistakes in what concerns the spin angular momentum of a circularly polarized light.

But it is merely his interpretation. Actually, the doubtless fact that the spin density of a perfect plane wave vanishes, only means that the perfect plane wave is nothing but a theoretical model, a certain idealization of real objects, and its validity is limited. There is no perfect infinite plane wave in reality, and any "physical" plane wave does carry spin.

There are different ways to reconcile the "plane-wave" idealization concept with more real situations, and one of them is to take into account that any observation of the plane wave field, any its interaction, even with a single atom, inevitably destroys its "ideal" character and "selects" certain finite fragment of its infinite cross section. Despite the ideal plane wave 'per se' carries no angular momentum density, the rigorously calculated angular momentum of this transverse fragment exactly equals to what is dictated by the homogeneous distribution of constant spin density across the plane wave. I guess, this was reported several times in a bit different forms; I refer to what I know better: A. Y. Bekshaev, Spin angular momentum of inhomogeneous and transversely limited light beams *Proc. SPIE* **6254** 56-63 (2006). Afterwards, this approach was described in reviews:

A. Bekshaev, M. Soskin and M. Vasnetsov, *Paraxial Light Beams with Angular Momentum* (New York: Nova Science Publishers, 2008) (see also arXiv:0801.2309);

A. Bekshaev, K. Bliokh, M. Soskin, Internal flows and energy circulation in light beams. J. Opt. 13, 053001 (2011).

Thus, the vanishing spin density of an ideal circularly polarized plane wave is completely compatible with its ability to carry angular momentum and to transmit it to absorptive media. References [14-16], which seem to have motivated the author's efforts, are not misleading, and there is no necessity to prove again the well established fact that a circularly polarized wave contains angular momentum. As a result, in its present form, the paper conveys no useful information. At the same time, if the author properly explains the aim and the meaning of his calculations and properly describes their place among other known results, the rewritten and reorganized materials can be considered anew.

Author's appeal

First, the referee must explain the difference between a "**perfect plane wave"**, which has no spin, and a **plane wave**, which carries spin.

This paper shows that an *ideal, perfect* circularly polarized plane wave travelling in z-direction and with infinite extension in the xy-directions *carries* spin density, just like such a wave carries energy-momentum density! Nobody knows this fact.

F.S. Crawford, Jr.: "A circularly polarized travelling plane wave carries angular momentum". But he does not know that an *ideal, perfect* circularly polarized plane wave carries spin density. He thinks that the ideal, perfect circularly polarized plane wave carries *only* energy and momentum densities given by the Poynting vector.

K. Y. Bliokh at al. consider evanescent waves. But they do not know that an ideal, perfect circularly polarized plane wave carries spin density.

A. Y. Bekshaev considers inhomogeneous and transversely limited light beams. But he does not know that an ideal, perfect circularly polarized plane wave carries spin density.

Do not reconcile the "plane-wave" idealization concept with more real situations because the ideal plane wave 'per se' carries spin density.

The perfection of a circularly polarized plane wave does not deprive the wave of the spin density, just like the perfection does not deprive the wave of the energy-momentum density.

It is important to show that the equation for absorption of the spin flux density (6.8) is quite similar to the equation describing the absorption of the mass flux density (4.2) for an ideal, perfect circularly polarized plane wave.

The given calculations show that spin is a natural property of an ideal, perfect circularly polarized plane electromagnetic wave, similar to energy and momentum.

Nobody used the spin tensor of an ideal, perfect circularly polarized plane wave in order to calculate the spin density of a circularly polarized plane wave with infinite extension.

The referee thinks that the spin density of a perfect plane wave vanishes because there is no perfect infinite plane wave in reality. But he does not explain how the "physicalness" supplies a plane wave with the spin density.

And I think that the report shows the importance of publishing of this paper.

Editor in Chief, Journal of Modern Optics

Dear Dr. Khrapko, I regret to inform you that the JMO board of editors has considered your appeal and has voted to uphold the rejection decision. We cannot consider further appeals on this particular manuscript.
Sincerely, Thomas G. Brown

Absorption of angular momentum of a plane electromagnetic wave

http://khrapkori.wmsite.ru/ftpgetfile.php?id=161&module=files
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We show that a dielectric or magnetic medium absorbs angular momentum if the medium absorbs a circularly polarized plane electromagnetic wave. This means that the wave contains the angular momentum, which is spin angular momentum, briefly; spin. And this fact is in accordance with the concept of a classical electrodynamics spin tensor. Lorentz transformations are used for energy, momentum, and angular momentum flux density because a moving absorber is considered.

Key Words: classical spin, circular polarization, spin tensor

PACS 75.10.Hk

1. Introduction

It was suggested as early as 1899 by Sadowsky [1] and as 1909 by Poynting [2] that any circularly polarized light contains angular momentum *density*. That is the angular momentum is present in any point of the light. The concept of angular momentum density seems to be confirmed by classical interference experiments [3 – 6]. Really, in these experiments, the angular momentum of the light was transferred to a half-wave plate, which rotated. So, work was performed. This (positive or negative) amount of work reappeared as an alteration in the energy of the photons, i.e., in the frequency of the light, which resulted in moving fringes. This proves that the work was performed in any point of the plate.

The concept of angular momentum density was confirmed theoretically in the frame of the Lagrange formalism. According to the formalism, this angular momentum density is *spin* density. The spin of electromagnetic waves is described by a spin tensor [7 - 9].

$$\Upsilon^{\lambda\mu\nu} = -2A^{[\lambda}\delta_{\alpha}^{\mu]}\frac{\partial\mathcal{L}}{\partial(\partial_{\nu}A_{\alpha})}, \quad (1.1)$$

where $\mathcal{L}$ is a Lagrangian and A^{λ} is the magnetic vector potential of the electromagnetic field. So, any infinitesimal 3-volume dV_{ν} contains spin

$$dS^{\lambda\mu} = \Upsilon^{\lambda\mu\nu}dV_{\nu}. \quad (1.2)$$

However, this spin tensor was discredited and eliminated by the Belinfante-Rosenfeld procedure [7 - 11], and the Poynting's and Sadowsky's concept was overrided. According to the nowday widespread opinion, angular momentum of electromagnetic field is moment of linear momentum only, and this moment of momentum sometime is named spin because of the Humblet transformation [12,13]. Below we cite a few typical examples of this opinion:

Heitler: "A plane wave travelling in z-direction and with infinite extension in the xy-directions can have no angular momentum about the z-axis, because Π is in the z-direction and $(\mathbf{r}\times\Pi)_z = 0$" [14] (Here Π denotes the Poynting vector).

Simmonds & Guttmann: "The electric and magnetic fields can have a nonzero z-component only within the skin region of this wave. Having z-components within this region implies the possibility of a nonzero z-component of angular momentum within this region. So, the skin region is the only in which the z-component of angular momentum does not vanish" [15, p. 227]

Allen & Padgett: "For a plane wave there is no (radial intensity) gradient and the spin density is zero" [16]

On the other hand, the Poynting's and Sadowsky's concept seems to be supported by a suggestion that a circularly polarized electromagnetic wave must induce specific mechanical stresses in any point of an absorber of the wave because of absorption of spin density [17]. Otherwise a considerable nonlocality of the electrodynamics threatens us: the concept "Spin is only in the skin region" implies that energy of light is absorbed everywhere in the absorber, but angular momentum is absorbed in the remote boundary of the wave only [18]. And that is more, it was shown that the Belinfante-Rosenfeld procedure is illegitimate and that the Humblet transformation proves nothing [17,19].

In this paper, we confirm the Poynting's and Sadowsky's concept by a new calculation.

Since 1905, when Einstein explained the photoeffect, it has become clear that an electromagnetic wave consists of photons. Photons have energy, momentum and spin (internal angular momentum), and if the wave is circularly polarized, spins of all the photons are directed in the same direction that is parallel to that of the momentum of the wave. Therefore, one can use such notions as volume density and flux density of momentum, energy, and spin as well as number of photons in an electromagnetic wave. Densities of the energy and momentum are quantitatively described by the Maxwell energy-momentum tensor. The density of the spin should be described by the spin tensor (1.1). The numeric density of photons is obtained either by dividing the energy density of a wave by the energy of a single photon $\hbar\omega$, or by dividing the spin density by the spin of a single photon $\hbar$ (if polarization is circular).

In a famous paper [20], the reflection of light from a moving boundary between two media was almost exhaustively investigated. In addition, in our previous paper, we have examined the laws of conservation of energy, momentum and spin for the incidence of a plane electromagnetic wave on a mirror [21]. In this paper, we consider the incidence of such a wave on the surface of a moving "symmetric absorber".

2. A symmetric absorber

We call "symmetric absorber" a medium, which is both dielectric and magnetic with $\varepsilon = \mu$. Such a medium does not require generating a reflected wave; this simplifies formulas.

So, let a plane monochromatic circularly polarized electromagnetic wave

$$\breve{\mathbf{E}} = E(\mathbf{x} + i\mathbf{y})\exp(ikz - i\omega t)\ \text{[V/m]}, \quad \breve{\mathbf{H}} = -i\varepsilon_0 c\breve{\mathbf{E}}\ \text{[A/m]}, \quad ck = \omega \tag{2.1}$$

impinges normally on a flat x,y-surface of the absorber, which is characterized by complex permittivity and permeability $\breve{\varepsilon} = \breve{\mu}$ (we indicate complex numbers and vectors by the *breve* mark) and moves along the z axis with a speed v.

As is well known, the wave (2.1) carries the volume density of mass-energy u, the flux density of mass-energy (the Poynting vector) Π, the volume density of momentum G, and flux density of momentum (pressure) $\mathscr{P}$, as described by the formulas

$$u = \frac{\varepsilon_0 E^2}{c^2}\left[\frac{\text{kg}}{\text{m}^3}\right], \ \Pi = G = \frac{\varepsilon_0 E^2}{c}\left[\frac{\text{kg}}{\text{m}^2 s}\right], \ \mathscr{P} = \varepsilon_0 E^2\left[\frac{\text{kg}}{\text{m}s^2} = \frac{\text{N}}{\text{m}^2}\right], \tag{2.2}$$

but because of Doppler Effect [22 § 48], our wave has lesser frequency and, according to [10], has lesser amplitude *relative to the moving absorber*

$$\omega' = \omega\sqrt{\frac{1-\beta}{1+\beta}}, \qquad E' = E\sqrt{\frac{1-\beta}{1+\beta}} \tag{2.3}$$

where $\beta = v/c$. So, relative to the absorber, the impinging wave is expressed by the formulas

$$\breve{\mathbf{E}}' = E'(\mathbf{x} + i\mathbf{y})\exp(ik'z - i\omega' t), \quad \breve{\mathbf{H}}' = -i\varepsilon_0 c\breve{\mathbf{E}}', \quad ck' = \omega' \tag{2.4}$$

Accordingly, the Poynting vector and the momentum flux density prove to be lesser relative to the moving surface

$$\Pi' = \frac{\varepsilon_0 E'^2}{c} = \frac{\varepsilon_0 E^2}{c}\frac{1-\beta}{1+\beta}, \quad \mathscr{P}' = \varepsilon_0 E'^2 = \varepsilon_0 E^2\frac{1-\beta}{1+\beta}. \tag{2.5}$$

3. The Lorentz transformations

However, from the viewpoint of an observer at rest, these latter quantities, i.e. mass-energy and momentum flux densities through the surface, have other values. These values must be found by the Lorentz transformations for coordinates of a 4-point and for components of 4-momentum

$$t = \frac{t' + vz'/c^2}{\sqrt{1-\beta^2}}, \quad z = \frac{z' + vt'}{\sqrt{1-\beta^2}}, \quad m = \frac{m' + vp'/c^2}{\sqrt{1-\beta^2}}, \quad p = \frac{p' + vm'}{\sqrt{1-\beta^2}}. \tag{3.1}$$

We denote these flux densities by $\Pi_0, \mathscr{P}_0$. Taking into account that densities satisfy the equations,

$$\Pi_0 = m/at, \ \mathscr{P}_0 = p/at, \ \Pi' = m'/at', \ \mathscr{P}' = p'/at', \tag{3.2}$$

where a is an area, which is not being transformed, and substituting values (3.1), when $z' = 0$, into expression (3.2), we get Lorentz transformations for the flux densities

$$\Pi_0 = \Pi' + v\mathscr{P}'/c^2, \ \mathscr{P}_0 = \mathscr{P}' + \Pi' v. \tag{3.3}$$

So, from the viewpoint of the observer at rest, the flux density of mass-energy, which enters into the absorber, equals

$$\Pi_0 = \Pi' + \frac{v\mathscr{P}'}{c^2} = \frac{\varepsilon_0 E^2}{c}\frac{1-\beta}{1+\beta} + \frac{v}{c^2}\varepsilon_0 E^2\frac{1-\beta}{1+\beta} = \frac{\varepsilon_0 E^2}{c}(1-\beta) \tag{3.4}$$

4. Filling of the space with mass

Flux density Π_0 (3.4) is lesser than flux density Π (2.2), which is brought by the incident wave. The difference between the mass fluxes (2.2) and (3.4) is spent on filling of the space that is vacated by the moving absorber. This filling requires a mass flux density, which we denote $\tilde{\Pi}$,

$$\tilde{\Pi} = uv = \frac{\varepsilon_0 E^2}{c^2} v = \frac{\varepsilon_0 E^2}{c}\beta . \qquad (4.1)$$

As a result, we obtain the simple equality

$$\Pi = \tilde{\Pi} + \Pi_0 = \frac{\varepsilon_0 E^2}{c} . \qquad (4.2)$$

But it is desirable to demonstrate the mechanism of the absorption of mass flux density Π' (2.5) in the symmetric absorber. See next section.

5. Absorption of energy and angular momentum

According to (2.4), the wave propagated in the absorber is described by the formulas

$$\breve{\mathbf{E}}' = E'(\mathbf{x} + i\mathbf{y})\exp(ik'\breve{k}z - i\omega' t'), \quad \breve{\mathbf{H}}' = -i\varepsilon_0 c\breve{\mathbf{E}}', \quad ck' = \omega' \quad \breve{k} = \sqrt{\breve{\varepsilon}\breve{\mu}} = \breve{\varepsilon} = \breve{\mu} = k_1 + ik_2 \qquad (5.1)$$

The mechanism of the absorption in dielectric was explained by Feynman [23]. According to the explanation, the rotating electric field $\breve{\mathbf{E}}' = \breve{E}'(\mathbf{x} + i\mathbf{y})\exp(-i\omega' t)$ exerts a torque $\tau = \breve{\mathbf{d}} \times \breve{\mathbf{E}}'$ on the rotating dipole moments of molecules $\mathbf{d}$ of the polarized dielectric and makes a work. The power volume density of this work is

$$w_e = \left|\breve{\mathbf{P}}_e \times \breve{\mathbf{E}}'\right|\omega' \ \ [\text{J/m}^3\text{s}], \quad \breve{\mathbf{P}}_e = (\breve{\varepsilon} - 1)\varepsilon_0 \breve{\mathbf{E}}', \qquad (5.2)$$

$\breve{\mathbf{P}}_e$ is the polarization vector, and $\breve{\mathbf{P}}_e \times \breve{\mathbf{E}}'$ [J/m^3] is a *torque volume density*. The calculation gives

$$w_e = \frac{\omega'}{2}\Re\{\breve{P}_{ex}\overline{E}'_y - \breve{P}_{ey}\overline{E}'_x\} = \frac{\omega'\varepsilon_0}{2}\Re\{(\breve{\varepsilon}-1)(\breve{E}'_x\overline{E}'_y - \breve{E}'_y\overline{E}'_x)\} = \frac{\omega'\varepsilon_0}{2}\exp(-2k'k_2 z)\Re\{(\breve{\varepsilon}-1)(-i-i)\}E'^2$$
$$= \omega'\varepsilon_0 \exp(-2k'k_2 z)\Im(\breve{\varepsilon}-1)E'^2 = \omega'\varepsilon_0\exp(-2k'k_2 z)k_2 E'^2 . \qquad (5.3)$$

Naturally, the rotating magnetic field of electromagnetic wave (5.1) makes the same work over rotating magnetic dipoles in the absorber.

$$w_m = \left|\breve{\mathbf{P}}_m \times \breve{\mathbf{H}}'\right|\mu_0\,\omega' \ \ [\text{J/m}^3\text{s}], \quad \breve{\mathbf{P}}_m = (\breve{\mu} - 1)\breve{\mathbf{H}}', \qquad (5.4)$$

$$w_m = \omega'\Re\{\breve{P}_{mx}\overline{H}'_y - \breve{P}_{my}\overline{H}'_x\}\mu_0 / 2 = \omega'\mu_0\Re\{(\breve{\mu}-1)(\breve{H}'_x\overline{H}'_y - \breve{H}'_y\overline{H}'_x)\}/2 . \qquad (5.5)$$

Substituting value (5.1) for the magnetic field into (5.5), we see that the work of the magnetic field is equal to the work of the electric field

$$w_m = \omega'\varepsilon_0\Re\{(\breve{\varepsilon}-1)(\breve{E}'_x\overline{E}'_y - \breve{E}'_y\overline{E}'_x)\}/2 = w_e . \qquad (5.6)$$

The energy flux density, which is carried to the surface of the absorber by the wave, can be obtained by the integration of the total power volume density, $w = w_e + w_m = 2w_e$, over z

$$\int_0^\infty 2w_e dz = 2\omega'\varepsilon_0\int_0^\infty \exp(-2k'k_2 z)k_2 E'^2 dz = \frac{\omega'\varepsilon_0}{k'}E'^2 = \varepsilon_0 c E'^2 = \Pi' c^2 \left[\frac{\text{J}}{\text{m}^2 s}\right]. \qquad (5.7)$$

So, the total energy flux density (5.7) coincides with $\Pi' c^2$ (2.5).

But we must recognize that the torque volume density[5] $\tau_{\sim} = \breve{\mathbf{P}}_e \times \breve{\mathbf{E}}' + \breve{\mathbf{P}}_m \times \breve{\mathbf{H}}'\mu_0$, which brings energy into the absorber, is also a volume density of the *angular momentum flux*, which enters into the absorber. The torque volume density $\tau_{\sim}$ produces specific mechanical stresses in the dielectric [17]. And, as the volume density of angular momentum flux, the torque volume density requires angular momentum flux density, which is brought onto the surface of the absorber by the

[5] We mark pseudo densities by index *tilda*. The torque volume density $\tau_{\sim}$ is a pseudo *density*, as opposed to the torque τ.

wave. We get this angular momentum flux density by integrating the torque volume density $\tau_{\sim}$ over z.

$$\Upsilon' = \int_0^\infty \left|\breve{\mathbf{P}}_e \times \breve{\mathbf{E}}' + \breve{\mathbf{P}}_m \times \breve{\mathbf{H}}'\mu_0\right| dz = \frac{1}{\omega'}\int_0^\infty (w_e + w_m) dz = \frac{\Pi' c^2}{\omega'} = \frac{\varepsilon_0 c}{\omega'} E'^2 \quad \left[\frac{\mathrm{J}}{\mathrm{m}^2}\right]. \tag{5.8}$$

Using formulas (2.3), we can express this angular momentum flux density in terms of the incident wave (2.1)

$$\Upsilon' = \frac{\varepsilon_0 c}{\omega'} E'^2 = \frac{\varepsilon_0 c}{\omega} E^2 \sqrt{\frac{1-\beta}{1+\beta}}, \tag{5.9}$$

And in order to transform it to the laboratory at rest, we must take into account that the angular momentum flux density satisfies the identities

$$\Upsilon_0 = J / at, \quad \Upsilon' = J' / at', \tag{5.10}$$

where a is an area, that is not being transformed, and $J = J'$ is an angular momentum relative to the axis z, that is not being transformed as well. Taking into account (3.1), equations (5.10) yield the angular momentum flux density that enters the absorber from the viewpoint of the observer at rest:

$$\Upsilon_0 = \Upsilon' t' / t = \frac{\varepsilon_0 c}{\omega} E^2 \sqrt{\frac{1-\beta}{1+\beta}} \sqrt{1-\beta^2} = \frac{\varepsilon_0 c}{\omega} E^2 (1-\beta). \tag{5.11}$$

The results of this Section concerning the absorption of energy and angular momentum in dielectric were first published in paper [24].

6. Calculation of the angular momentum flux density of the electromagnetic wave

By the fact that angular momentum (5.11) is absorbed under every square meter of the absorber surface per second, one can conclude that the angular momentum is carried to the surface by the wave (2.1). To calculate the corresponding angular momentum flux, i.e. spin flux, it is natural to use the electrodynamics canonical spin tensor [7,8]

$$\Upsilon^{\lambda\mu\nu} = -2A^{[\lambda} F^{\mu]\nu}, \tag{6.1}$$

here $F^{\mu\nu}$ is the electromagnetic field tensor, and A^{λ} is the magnetic vector potential.

Spin flux density, which is directed along z-axis to xy surface, is given by the component

$$\Upsilon^{xyz} = -2A^{[x} F^{y]z} = A_x H_x + A_y H_y \ [\mathrm{J/m^2}]. \tag{6.2}$$

Note that the lowering of the spatial index of the vector potential is related to the change of the sign in the view of the metric signature $(+---)$. Since $A_k = -\int E_k dt = -iE_k / \omega$ for a monochromatic field, densities (6.1), (6.2) can be expressed through the electromagnetic field:

$$\Upsilon^{xyz} = (-iE_x H_x - iE_y H_y)/\omega. \tag{6.3}$$

So, in our case, in addition to (2.2), we have spin flux density

$$\Upsilon = \langle \Upsilon^{xyz} \rangle = \Re\{-iE_x \overline{H}_x - iE_y \overline{H}_y\}/2\omega = \frac{\varepsilon_0 c}{\omega} E^2 = \frac{\Pi c^2}{\omega} \tag{6.4}$$

for the incident wave (2.1). This quantity, (6.4), is larger than the angular momentum flux density Υ_0 (5.11), which enters into the absorber. The difference between the angular momentum fluxes (6.4) and (5.11) is spent on filling of the space vacated by the absorber moving at the speed v. This filling requires angular momentum flux density, which we denote $\tilde{\Upsilon}$. Angular momentum volume density is given by the component

$$\Upsilon^{xyt} = -2A^{[x} F^{y]t} = -A_x D_y + A_y D_x = (iE_x D_y - iE_y D_x)/\omega \tag{6.5}$$

of the spin tensor (6.1). Using time averaging, we get

$$\langle \Upsilon^{xyt} \rangle = \Re\{(iE_x \overline{D}_y - iE_y \overline{D}_x)/2\omega = \varepsilon_0 E^2 / \omega \ [\mathrm{Js/m^3}]. \tag{6.6}$$

So, the filling of the space requires

$$\tilde{\Upsilon} = <\Upsilon^{xyt}> v = \frac{\varepsilon_0 E^2}{\omega} v = \frac{\varepsilon_0 c E^2}{\omega} \beta . \qquad (6.7)$$

As a result, we obtain a simple equality

$$\Upsilon = \tilde{\Upsilon} + \Upsilon_0 = \frac{\varepsilon_0 c E^2}{\omega} , \qquad (6.8)$$

which is similar to (4.2)/

7. Conclusion

The given calculations show that spin is a natural property of a plane electromagnetic wave, similar to energy and momentum. If we recognize the existence of photons with momentum, energy and spin in a plane electromagnetic wave, we have to admit the existence of the spin density in the wave. The nowday widespread opinion has to be revised in view of the critisism.

I am eternally grateful to Professor Robert Romer, having courageously published my question: "Does plane wave really not carry spin?" [25].

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A paper **Circularly polarized beam carries the double angular momentum**
TMOP-2013-0483 http://viXra.org/abs/1308.0147
was rejected by **Journal of Modern Optics** anonymously without review on September 13, 2013: "Our editorial team have now considered your paper but feel the topic discussed is not best suited to the Journal of Modern Optics. Editorial Office"

This decision was strange because JMO published a paper on this topic: Khrapko R.I. "Mechanical stresses produced by a light beam", *J. Modern Optics* 55, 1487-1500 (2008). So, the decision required an explanation. And we found the explanation. The explanation was presented in this message to JMO.

Dear Prof. Jonathan Marangos Editor in Chief JMO,
Editorial Office rejected the paper TMOP-2013-0483. But we hope you remember that your Reviewer-2007 wrote about another paper, "Mechanical stresses produced by a light beam":
- "There is an additional spin angular momentum for the photon, that is not present in standard (Maxwell-based) theory".
- "This is a difficult paper to judge. It attempts to clarify and correct some questions in one of the 4 or so century-old controversies in classical electrodynamics, perhaps the major one of interest in modern optics. I think the paper, almost in the present form, would be a useful addition to the research literature on the topic, and I'm willing to recommend publication with minor changes. This is despite the paper being in error, in my opinion. The paper is on a topic where the literature is literately riddled with error, confusion, and dispute. The topic is of interest in practical issues in optical micromanipulation and of theoretical interest in the foundations of field theory and classical electrodynamics. Given the confused situation of the literature on this topic, I'm prepared to recommend the paper for publication despite the errors - it won't make things worse, and does make, in my opinion, a positive contribution.
- The main error in the paper, in my opinion, is one of double-counting. The angular momentum transport by a light beam can be deal with, in most cases, either in terms of the moment of the Poynting vector, or by the spin + orbital angular angular momenta, as done by Humblet. For example, there is a page of problems in Jackson, 3rd ed, devoted to this point. The author adds the two together, which is wrong. However, I don't think this will lead readers into error, so I don't see this as a real obstacle to publication".
Nevertheless the Reviewer admitted publishing of the paper because he was sure that the paper being in error and would not damage the interests of the physical authorities. He wrote:

As a result, the Reviewer admitted publishing of the paper because he was sure that the paper being in error and would not damage the interests of the physical authorities.

And you, Prof. Jonathan Marangos, wrote to the author:
- "September 9, 2007. We are pleased to accept your paper in its current form and we look forward to receiving further submissions from you".

However, Reviewer-2009, when considering the next submission *), also was sure that the paper being in error, but, unfortunately, as opposed to Reviewer-2007, he believed that "the conventional (Maxwell and Poynting - based) theory of optical angular momentum is in excellent agreement with all recent experiments and there is no need nor evidence for any correction of the type envisaged by the author". And the paper was rejected.

Now an anonymous Editorial team has recognized that the conclusion presented in this new paper is true. The team requested a translation of an old paper **). The team could give no objections against the papers. And then the team rejected this new paper because this paper would damage the interests of the physical authorities.

This is the explanation of the rejection!

*) Khrapko R.I. "Experiments for Determination of Angular Momentum Flux Density". This paper is now published: "On the possibility of an experiment on 'nonlocality' of electrodynamics", *Quantum Electron*, 2012, 42 (12), 1133 http://khrapkori.wmsite.ru/ftpgetfile.php?id=34&module=files, viXra:1307.0110 . See also http://khrapkori.wmsite.ru/ftpgetfile.php?id=46&module=files (replies of journals are presented), http://www.mai.ru/science/trudy/published.php?ID=28833 (2012).

**) Khrapko R.I. "Circularly polarized beam carries the double angular momentum. (2003)" http://www.mai.ru/science/trudy/published.php?ID=34422 (in Russian). See http://viXra.org/abs/1309.0090