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Photon-photon scattering and related phenomena.

Experimental and theoretical approaches: The early period

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Abstract

We review the literature on possible violations of the superposition principle for electromagnetic fields in vacuum from the earliest studies until the emergence of renormalized QED at the end of the 1940's. The exposition covers experimental work on photon-photon scattering and the propagation of light in external electromagnetic fields and relevant theoretical work on non-linear electrodynamic theories (Born-Infeld theory and QED) until the year 1949. To enrich the picture, pieces of reminiscences from a number of (theoretical) physicists on their work in this field are collected and included or appended.

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1 Introduction

Light has caught the imagination of men since the earliest historic times and theories on its nature probably have an even long history. The physical world around us to a large extent is being perceived by us by means of (visible) light and also the discourse of physical theory-building is strongly influenced by our anthropomorphic capability “to see”. A hypothetic intelligent species without such a visual capability probably would approach physical theory-building in a different manner than we do - trying to figure out the nature of that “dark matter” that is visible to mankind. To us, light and its interaction with (charged) matter is prototypical, and so is the most advanced to date theory describing it - quantum electrodynamics (QED). Our visual perception of the world (and also many physical experiments) is resting on two pillars: the interaction of light with charged particles whose strength is ruled by the fine structure constant, and the (for all practical purposes) non-interaction of light with itself described by the superposition principle. In the literature, various formulations of the superposition principle can be found. As we are both concerned with experimental and theoretical work to us the superposition principle is more than a mathematical rule related to the linearity of the equations describing a physical phenomenon. Quite generally, we understand the superposition principle as the principle that two physical influences can be superposed without impeding each other. In this sense, in our context it can be understood as a specific non-interaction principle – a non-self-interaction principle.

That the superposition principle for light is something special to be thought about has been recognized long ago. In 1604, Johannes Kepler wrote in his book *Ad Vitellionem Paralipomena, Quibus Astronomiae Pars Optica Traditur*^[a]: “The rays of light neither mutually color each other, nor mutually illuminate each other, nor mutually impede each other in any way. . . . This is just like one physical motion’s not impeding another.” It seems that Kepler is the first to explicitly mention this property of light: His intellectual predecessor, Erazmus Witelo (Vitellio, Vitello; 13th century) Kepler refers to in the title of his book does not mention this property in book II of his *Perspectiva* [165, 167] where one would expect such an observation to occur^[b]. Somewhat later than Kepler, in 1690, Christiaan Huygens commented in

^[a]Proposition 26 ([161], p. 23, reprint (1859) p. 142, reprint (1939) p. 32: cf. our App. A, p. 37; English transl. [164], p. 37)

^[b]It is rather Ibn al-Haytham (Alhazen; “the father of optics”) who might be considered as having observed and described earlier the superposition principle for light in some rudimentary form. A. I. Sabra notes ([168], p. 207, footnote 29): “Ibn al-Haytham described an experiment (the well-known *camera obscura experiment*) to show that beams of coloured light do not mix, and therefore do not affect one another, when they meet in space (at the opening of ‘the dark place’).” Ibn al-Haytham described his conclusions the following way (For the Arabic text see [169], Latin: [166], book I, chap. 5, item 29, p. 17, cf. our App. A, p. 37. For a reprint of the Latin text see [171], book I, chap. 7, p. 57, item [6.87]. We quote here from the English translation [172], book I, chap. 7, p. 380, item [6.87]; for another English translation see [170], vol. I, book I, chap. 6, item I 116b, p. 91.): “Therefore, the lights do not mix in air; instead, each of them extends along straight lines; and those lines are parallel, or they intersect, or they have various [other] orientations. And

his *Traité de la Lumière*^[c]: “Another property of waves of light, and one of the most marvellous, is that when some of them come from different or even from opposing sides, they produce their effect across one another without any hindrance.” At the beginning of the 19th century the superposition principle led Thomas Young to the formulation of the principle of interference within the framework of the wave theory of light [178]. However, while within the framework of the wave theory of light the superposition principle must have been more or less natural, for the proponents of the rival model – the corpuscular model of light developed by Descartes and Newton – the superposition principle required special consideration. Sergeï I. Vavilov writes on this account^[d]: “The reproach often made in the XVIII. century to the Newtonian theory consisted just in saying that the collisions of the light corpuscles, i.e., a violation of the superposition, should be observed. An answer to this difficulty was the admission of the extreme smallness of the corpuscles: «I know – Lomonosov³^[K.S.: orig. footn.] wrote addressing the defenders of the corpuscular hypothesis – that you divide the material of light into such fine particles and place them in universal space with so little density that the whole quantity can be compressed and packed in the porous crevices of one grain of sand.»”.

In the 19th century, the wave theory of light got the upper hand over the corpuscular model in explaining optical phenomena and James Clerk Maxwell with his equations finally brought mathematical clarity to electromagnetic phenomena, including the propagation of electromagnetic waves and specifically visible light. The phenomenon of the non-self-interaction of light (in vacuum) described, for example, by Kepler and Huygens received its mathematical explanation in terms of the linearity of the Maxwell equations in vacuum. However, as Faraday discovered in material (polarizable) media electromagnetic fields may exert an influence on each other: In a magnetic field, a rotation of the plane of polarization of linearly polarized light propagating along the direction of the magnetic field can be observed (Faraday effect). Consequently, the linearity of the Maxwell equations has a restricted range of validity. Besides the Faraday effect, the discovery of the (electro-optic) Pockels and Kerr effects and the (magneto-optic) Voigt, Majorana, and Cotton-Mouton effects (birefringence in a magnetic field for propagation of light perpendicular to

the form of each light-source radiates along all the [straight] lines that can be extended from it through the air, and in accord with this [the resulting forms of light] do not mingle in the air, nor is the air tinted by them; rather, they merely pass through its transparency, and the air does not thereby become transformed.”. Witelo covers the camera obscura experiment by al-Haytham in an abbreviated manner without clearly expressing the superposition principle aspect we are interested in (cf. [165], book II, proposition 5, p. 40, reprint [166], p. 64, reprint [167], pp. 242/243, English translation: [167], p. 47).

^[c][173], p. 20: cf. our App. A, p. 37; English transl. [174], pp. 21/22 (We owe this quote Vavilov [11]).

^[d][11], p. 555, reprint [175], p. 234: cf. our App. A, p. 37; English transl. [11], arXiv:1708.06817/hal-01599214, p. T-1 (= P-3). Also see [176], part 2, § 2.

³^[K.S.: orig. footn.] М. В. Ломоносов, Слово о происхождении света. Собрание разных сочинений, ч. III [M. V. Lomonosov, Slovo o proiskhozhdenii sveta. Sbranie raznykh sochinenii, ch. III], 1803, p. 155. (K.S.: [179])

it) showed that material media can be polarized by electromagnetic fields in such a manner that the superposition principle for electromagnetic fields does not apply for material (polarizable) media in general (For references concerning these effects see [180, 181]). However, matterless space, the vacuum, remained immune from such effects in the view of physicists.

With the advent of the quantum theory at the beginning of the 20th century the corpuscular model of light made a surprising return with the emergence of the concept of the photon. The particle-wave dualism characteristic for all quantum phenomena led to a dialectical synthesis of the wave and corpuscular models of light. However, once the particle-like aspects of light had been recognized the century-old problem of the corpuscular model of light reemerged. What about the scattering of corpuscles of light – photons – among each other? Qualitative investigations of this problem began to emerge. The first theoretical attempt to study this problem was published in 1925 by Konstantin N. Shaposhnikov [8] by writing down the quantum mechanical equations for energy-momentum conservation for the photon-photon scattering process. Shaposhnikov’s main purpose was to emphasize that these equations allow solutions which correspond to a non-violation of the superposition principle. In 1926, Louis de Broglie then pointed out ([9], Chap. XI, Sec. 2, pp. 96-98; cf. our Appendix B, p. 42) that these equations also allow solutions which correspond to nontrivial scattering events between two photons in deviation from the superposition principle. This point has further been elaborated in a short contribution by Arthur L. Hughes and George E. M. Jauncey [10] in 1928. Vavilov, in 1928, discussed the status of the superposition principle for light from an experimental point of view by reporting on laboratory experiments of his own and invoking extraterrestrial considerations by means of an analysis of the problem of the solar corona ([11], cf. our subsecs. 2.1 and 2.3). The article by Vavilov was followed by a public exchange of comment and response between Shaposhnikov and Vavilov [13, 14]. In his reply ([14], p. 395, p. T-3 (= P-5) of the English transl.), giving credit for this consideration to Yakov I. Frenkel Vavilov pointed out that the superposition principle for light should be violated, in principle, in any case due to the (negligibly small) gravitational interaction of two quanta of light. The same argument had been made in 1928 already by Léon Rosenfeld and Enos E. Witmer ([12], p. 521) in an article in which they considered from a qualitative point of view the role of collisions among photons for the discussion of black body radiation.

However, the physical mechanism for photon-photon interaction processes and their quantitative details remained beyond consideration for a couple of further years. In 1933, Otto Halpern [26] finally proposed that virtual electron-positron pairs could be at the origin of photon-photon collisions. While this clarified the qualitative picture to be applied for the description of photon-photon scattering, only the early development of quantum electrodynamics (QED) provided physicists with the theoretical tools for a quantitative answer: It was finally given by two students of Werner Heisenberg, Hans Euler and Bernhard Kockel, who calculated

in 1935 the leading nonlinear corrections to the Maxwell equations in vacuum [47]. Within the framework of QED, it turned out that photon-photon scattering as a characteristic feature of a nonlinear electrodynamic theory has a very low probability for all practical purposes. Once the theoretical picture had been established the challenge emerged to demonstrate experimentally consequences of the violation of the linearity of Maxwell equations in vacuum, i.e., of the violation of the superposition principle for light (or, speaking more generally, for electromagnetic fields). The processes of Delbrück scattering (elastic scattering of a photon in the Coulomb field of a nucleus) and photon splitting (in an external field) have meanwhile experimentally been confirmed (cf. [182, 183]). The phenomenon of photon-photon scattering itself, however, has escaped experimental observation for many decades and has been demonstrated with sufficiently high statistics by the ATLAS collaboration in 2019 only [184] (after evidence for it had been seen for the first time at CERN by the ATLAS collaboration in 2017 [185] and then the CMS collaboration in 2018 [186]). This remarkable success underscores that the demonstration of such a fundamental physical phenomenon as photon-photon scattering is still a problem at the edge of current experimental and observational capabilities (for some other recent development see [187]).

There is a continuous current, varying in intensity over time, of experimental and theoretical research in the field of nonlinear electrodynamic phenomena in vacuum. The main motivation for experimental work derives from the prominent role electromagnetic phenomena play in the physical world we live in. Theoretical studies often have a wider set of motivations which are often linked to the changing directions of theoretical thinking. New research can successfully only be based on the knowledge of the achievements and failures of past generations of scientists. While the main publications from the past in the field of nonlinear electrodynamics in general and of QED in particular are well known many details of the early thinking and experimentation concerning photon-photon scattering and related phenomena seem to be largely forgotten. It is the purpose of the present review to collect as completely as possible the early literature on this subject as a source and inspiration for further research. The time span covered reaches from the earliest publications that can be linked to the problem of nonlinear electrodynamics up to 1949, i.e., the end of the 1940's, which roughly marks the begin of a new period in the history of theoretical physics with the emergence of renormalized quantum electrodynamics. Of course, the year 1949 is somewhat arbitrarily chosen based on an analysis of the occurrence of relevant literature references. In a certain way, the short review article by Kunze in 1949 [155] marks the end of the period the present exposition is concerned with.

The present review has a mixed character. On one hand, primarily it is written as a literature review. On the other hand, it is also a piece of science history. To illuminate various social and science history aspects we quote extensively from a number of different sources. This rather unconventional set-up serves a twofold purpose. First of all, it provides the reader with a more complex and first-hand

picture of the early developments. The second purpose consists in collecting the widely scattered pieces of text for the convenience of the reader in one place. Some of the early pieces of text have been translated into English to make them more easily accessible to the current and future generations of physicists.

The review is split in a section on early experimental work and a section on theoretical studies in nonlinear electrodynamics. Corresponding to the historic course of research, we cover both Born-Infeld electrodynamics as a (mainly) classical field theory and quantum electrodynamics which gives rise to an effective action by means of which contact can be made with a classical theory as Born-Infeld electrodynamics. However, the relation between both theories is more than a historic one. Also modern research benefits from viewing both theories as special instances of nonlinear electrodynamics because this allows to elucidate more easily general principles. The early literature on Born-Infeld electrodynamics has been included in the list of references somewhat more broadly than that from QED. As there does not seem to exist any comprehensive review of the early developments of Born-Infeld theory this choice seemed to be appropriate.

The list of references is split into two parts. One part arranged according to the year of publication contains the main body of references related to photon-photon scattering and related nonlinear electrodynamic phenomena up to 1949. Most of these references are cited and commented in the main body of our text, very few references are only listed in the bibliography for completeness and are not mentioned elsewhere [60, 67, 157–160]. The references in the main bibliography represent the present literature review in the narrow sense. All further references cited are collected in a separate list of (auxiliary) references. We deliberately cite literature after 1949 only once this seems absolutely to be necessary for the presentation or discussion. Consequently, most of the more recent relevant literature from 1950 onwards is absent. The main list of references is supplemented by a list of author names where for identification purposes the first names and, if known, the dates of birth and death are given. If available, we provide for each name a link to further information. For the convenience of the reader, we rely primarily on Wikipedia articles. Preference has been given to English language articles. If an English language article was not existent we have tried to make some other reasonable language choice. If no Wikipedia article was available at all, a link to some other information page on the Internet has been selected. In a number of cases, no appropriate information on the Internet was available. We then make reference to some printed obituary. In a small number of cases, we had to restrict ourselves to links to VIAF (Virtual International Authority File, OCLC) or some related source. Finally, for very few author names, we were unable to trace any further author information.

2 Experiment

In the period under consideration, experimental work concerning the study of photon-photon scattering and related phenomena has been fueled by a number of different developments in physics. There have been two main directions of experimental work:

1. Experimental work concerning the study of photon-photon scattering in the narrow sense, i.e., direct searches for experimental signatures of the scattering of light by light.
2. The experimental study of the propagation of light (photons) in strong (electromagnetic) fields. This main direction of research can historically be divided into 3 subcategories:
 - A. The dependence of the propagation of light on the intensity of the light wave.
 - B. The propagation of light (photons) in macroscopic, constant magnetic and electrical fields.
 - C. The propagation/scattering of photons in the Coulomb field of nuclei.

Finally, it seems to be appropriate to add as a further direction of experimental work:

3. Considerations related to extraterrestrial and astronomical observations.

In the following subsections arranged according to the above classification we will give an overview over the experimental and observational work up to the end of the 1940's. Early experimental and observational work on photon-photon scattering and related phenomena has been scarce. We have tried to cover the relevant literature as completely as possible and in the subsections below we will refrain from making any further statements to the effect that no further relevant work is known to us.

2.1 Photon-photon scattering

The first attempt to directly observe the scattering of photons by photons in an experiment seems to have been undertaken in 1928 in the Soviet Union by S. I. Vavilov (Institute of Biological Physics, Moscow). In a contribution read to the 6. Congress of Russian Physicist in Moscow on August 6, 1928 Vavilov reports^[el]: “Under laboratory conditions, the highest instantaneous radiation densities can certainly be obtained by means of the light of a condensed spark. Concentrating this light with a lense, instantaneous values of the light energy density that exceed

^[el][11], § 2, pp. 556/557, reprint [175], p. 236: cf. our App. A, p. 37; English transl. pp. T-2/T-3 (= P-4/P-5). Also cf. his note [18].

the corresponding value on the surface of the sun can be achieved easily. In this case, the average density is small due to the short duration and rareness of the sparks, but the hypothetical effect of the “collisions” of light quanta must be proportional to the square of the instantaneous density, therefore, a spark turns out to be considerably more advantageous than, for example, an arc. Preliminary experiments with a spark the light of which met in an evacuated container did not uncover any noticeable scattering. These observations have been carried out with the usual precautions, in front of distant container walls covered with black velvet; for control, the experiments have been repeated with the light of an incandescent lamp that delivered the same average radiation density; in both cases the result has been equally negative.”.

Shortly thereafter, in 1930, A. L. Hughes and G. E. M. Jauncey (Washington U., St. Louis, USA) published a somewhat more elaborate description of a similar experiment to detect collisions of photons [16, 17]. In difference to Vavilov, they used (intense) light from the sun to perform the experiment. Two light beams were allowed to meet at an angle of 120° and the observation for scattered light was performed with the dark-adapted eye in the plane of the scattering beams at the (forward) direction of the bisector of the angle between them. In their experiment, Hughes and Jauncey took into account that with the chosen geometric set-up light resulting from photon-photon collisions would emerge with a higher frequency according to the quantum-mechanical laws of energy-momentum conservation in the collisions. In the experiment, no experimental sign of photon-photon collisions was found and Hughes and Jauncey give as bound for the cross section σ of photon-photon scattering $\sigma < 3 \times 10^{-20} \text{ cm}^2$.

Interestingly, the article by Hughes and Jauncey [17] is not only followed by a short note by Vavilov [18] pointing out the results of his earlier experiments [11] but also by a short note by A. K. Das (Alipore Observatory, Calcutta, India) [20] giving details of an earlier (unpublished) idea for performing an experiment to study photon-photon scattering. Noting that due to the (likely) miniscule size of the effect photon-photon scattering cannot be observed by optical methods (cf. the analogous comment by Vavilov: [11], § 2, p. 558, p. 237 of the reprint, p. T-4 (= P-6) of the English translation), Das proposed to observe single (scattered) photons by means of “Elektronenzählrohren” (electron counter tubes) he had constructed for the investigation of gamma and cosmic rays. From a modern point of view, it is also interesting to note that Das envisioned the experiment to be performed with X-rays or gamma-rays (and not with visible light for which the cross section for photon-photon scattering is smaller).

The experiment in 1930 by Hughes and Jauncey was followed in 1933 by an analogous experiment performed by F. L. Mohler (Bureau of Standards, Washington, D. C., USA) [27] which differed from that of Hughes and Jauncey geometrically by the angle between the scattering light beams (180° in the experiment by Mohler

versus 120° in the experiment by the former; also see the corresponding comment by Hughes and Jauncey [39]). Mohler relied in his experiment on the light of projection lamps and the observation for scattered photons was performed with the human eye in the direction perpendicular to the joint axis of the two scattering light beams. The result of the experiment was negative and Mohler expressed the result in his article in terms of a limit on the cross section σ for photon-photon scattering ($\sigma < 6 \times 10^{-17} \text{ cm}^2$).

The following logical step in the experimental search for the existence of photon-photon collisions has been made in two Master theses: the human eye as detector of light (radiation) is being replaced by a photographic film. In 1937, B. Castaldi (Clark University, Worcester, MA, USA) investigates the problem of photon-photon scattering for visible light [105] (thesis advisor: P. M. Roope). In the experiment of Castaldi, a sodium Lab-arc is used as source of light (with a wavelength of approximately 589 nm). Two beams of light met at an angle of 60° and the photographic film used as detector of scattered light was placed in the plane of the scattering beams at the (forward) direction of the bisector of the angle between them (as in the experiment by Hughes and Jauncey). In the (final) trial (after the design phase), the photographic plate was exposed for 28 days (672 hours) and then developed. No trace of scattered light was found. Castaldi estimates that his method was 661.6 times as sensitive as that of Hughes and Jauncey relying on the human eye as detector. In 1940, to study the problem of photon-photon collisions R. V. Wiegand (Montana State College, Bozeman, MT, USA) uses X-rays for which, according to Euler and Kockel [47], the cross section ($\sim \omega^6$, where ω is the frequency of the scattering light quanta) is larger than for visible light [138] (thesis advisor: A. J. M. Johnson). The experiment has been performed with X-rays of a wavelength of 1.473 \AA ($= 0.1473 \text{ nm}$) and for an collision angle of $28^\circ 8,6'$. “X-ray film was placed on the six sides of the collision point and long exposures taken to determine if radiation was given off in any direction.” The maximal exposure time was 25 hours but “no “collision” radiation of sufficient amount to register on the photographic film was found” (both quotes are from the abstract of [138]).

2.2 Propagation of light in strong electromagnetic fields

2.2.1 Influence of the intensity on the propagation of light

In the late 19th/early 20th century the question has been studied if the speed of light might depend on the intensity of the propagating light wave. Experiments by J. J. Müller (University of Leipzig, Germany) performed with visible light and published in 1872 [1] indicated that the speed of light (in air) increases with increasing frequency and intensity (cf. the tables on pp. 107, 120 of [1]). The intensity variations studied by Müller were not larger than 1:10. Müller used interference experiments to investigate the dependence of the wavelength λ of an incident (monochromatic,

with frequency f) light beam on its intensity and inferred from it a corresponding variation in the speed of light $c = f\lambda$. Such a phenomenon of the intensity dependence of the speed of light (in vacuum) would clearly represent a violation of the superposition principle and would – on the theoretical side – correspond to a Lagrangian for the (gauge) field describing the light wave which is not quadratic in this field.

Contemporary physicists apparently had been aware of the potential significance of the results of Müller. Not long after the publication of his work [1] they have checked his assertion in other experiments with higher precision and found no indication for any intensity dependence of the speed of light hereby ruling out any noticeable self-interaction of a light beam with itself (F. Lippich, University of Prague, Austria: [2]; H. Ebert, University of Erlangen, Germany: [3]; Th. E. Doubt, University of Chicago, USA: [6]). Ebert [3] besides giving the results of his experiments also uses astronomical arguments (pp. 381-383) to infer that the speed of light cannot depend on the intensity of the light wave in any significant way (cf. our subsection 2.3). Doubt achieving in his experiments light intensity variations between 1:43000 and 1:290000 concluded that any corresponding variation in the speed of light, if any at all, must be smaller than roughly one part in one billion.

2.2.2 Propagation of light in macroscopic, constant magnetic and electrical fields^[f]

The earliest experiment to be mentioned in this section belongs to a time before the advent of the special theory of relativity. In the year 1900, R. A. Fessenden (Western University of Pennsylvania, Pittsburgh, USA) relied on an aether model to reason ([4], pp. 87/88) that an electrostatic field should lead to an increase in the speed of light in vacuo in the direction of the applied electric field. Two years later, Fessenden reported a positive result obtained by him in a preliminary experiment to check his assertion [5]. It seems that neither Fessenden nor any other researcher has later returned to this subject. This is not very surprising in view of the fact that in 1905 Albert Einstein started to revolutionize thinking on fundamental physics. While the aether as a vacuum model had to be abolished even Albert Einstein seems to have further thought about the possibility that the speed of light in vacuo might depend on external electromagnetic fields.

Information in this respect comes from a reminiscence by P. L. Kapitsa of a conversation he has had with Albert Einstein on the occasion of a visit^[g] of the latter

^[f]For a different discussion of the experiments by Watson [15] and Farr and Banwell [21, 135] dealt with in this subsection see p. 11 of [188].

^[g]This meeting took place at an unknown date, somewhen during the period between 1922 and 1934 when Kapitsa worked at the University of Cambridge - probably, after 1929 when the

to the Cavendish Laboratory of the University of Cambridge. His report provides us with an interesting glimpse into the thinking of Albert Einstein. Kapitza recalls^[h]: “In the 1930s, in Cavendish’s laboratory, I developed a method of obtaining magnetic fields one order stronger than had previously been attained. In a conversation Einstein tried to persuade me to study experimentally the influence of a magnetic field upon the velocity of light. Such experiments had been conducted, and no effect was discovered. In my magnetic fields it was possible to raise the limit of accuracy of measurement by two orders of magnitude, because the effect was dependent on the square of the intensity of the magnetic field. I protested to Einstein that according to the existing picture of electromagnetic phenomena, I could not see from whence such a measurable phenomenon would come. Having found it impossible to prove the need for such experiments, Einstein finally said, “I think that *der liebe Gott* could not have created the world in such a fashion that a magnetic field would be unable to influence the velocity of light.” Of course, it is hard to counter that kind of argument.”

A first experiment investigating the propagation of light in a (constant homogeneous) transverse magnetic field had been carried out in 1929 by W. H. Watson [15] at the Cavendish Laboratory in Cambridge, UK. This experiment predates the development of the theory of quantum electrodynamics. The main motivation for the experiment has been to look for the existence of a magnetic moment of the photon. The experiment has been carried out with a magnetic field strength (magnetic induction) of 10 000 gauss (= 1 tesla = 1 T) (for reference, the QED critical field strength is $B_{\text{cr}} = \frac{c^2 m_e^2}{e\hbar} \sim 10^9 \text{ T}$, m_e is the electron mass). The interaction region between the strong magnetic field and the light beam used for observation was located in a Fabry-Pérot cavity from which air had been pumped out (The quality of the obtained vacuum is not described in [15].). The interference pattern whose potential change has been observed was produced by polarized, monochromatic (visible) light of a wavelength of 585.2 nm. The null result that was obtained in the experiment yields a bound on the magnetic moment of the photon μ_γ of $\mu_\gamma < 1.4 \cdot 10^{-22} \text{ emu}$ (= $1.4 \cdot 10^{-25} \text{ Am}^2$). Equivalently, the null result entails that the change in the refractive index of the vacuum under the influence of the magnetic field is less than $4 \cdot 10^{-7}/\text{T}$.

Three years later, in 1932, C. C. Farr and C. J. Banwell of the Canterbury University College, Christchurch, New Zealand, published the description of an experiment designed to study the “Velocity of propagation of light in vacuo in a transverse magnetic field” [21]. This experiment relied on a different experimental set-up than

experiment by W. H. Watson [15] had been performed (see further below). The question when this conversation took place precisely must rest with historians of science. For an account of the visits of Einstein to Oxford see [189].

^[h][190], p. 31, [191], p. 40, reprints: 1. [191], p. 40. 2. [192], 3. ed. p. 375, 4. ed. p. 374, English transl. [194], p. 9, reprint [195], p. 317; we quote here the English translation, for the original Russian text see our App. A, p. 38. I owe this quote Yu. M. Poluektov [196], p. 6.

that performed by Watson. A Jamin refractometer was used where one unpolarized, monochromatic light beam (of a wavelength of 546.1 nm) passed through the strong magnetic field while the other (parallel, of the same wavelength) beam only experienced a weaker leakage field. Using this set-up Farr and Banwell achieved a roughly one order of magnitude higher sensitivity than Watson. The strength of the magnetic field amounted to 17 992 gauss (= 1.7992 tesla). The quality of the obtained vacuum in the interaction region is given as 0.005 mm of mercury (= 0.005 torr = 0.67 Pa) and the authors conclude from the null result they obtained that the change in the refractive index of the vacuum under the influence of the magnetic field is less than $2.7 \cdot 10^{-8}/\text{T}$.

Further eight years later, in 1940, Banwell and Farr published an account of an improved experiment of the same type performed using a yet different set-up [135], namely, a Michelson interferometer. Here one of the two perpendicular optical arms was placed in the strong magnetic field while the other did not experience the influence of any significant magnetic field at all. In the Michelson interferometer unpolarized, monochromatic light of a wavelength of $\lambda = 546.1$ nm was propagating. The intensity of the applied magnetic field is given as 19 917 oersted (corresponding to a magnetic induction of 1.9917 T in vacuo). The quality of the vacuum in the Michelson interferometer is stated as 0.05 mm of mercury (= 0.05 torr = 6.7 Pa). With the probable error taken into account, Banwell and Farr obtain as result of their Michelson interferometer experiment a non-null result. In the applied magnetic field of roughly 2 T they find an increase in the speed of light by (0.3431 ± 0.1856) m/s. The estimated error corresponds to a change in the refractive index of $3.1 \cdot 10^{-10}/\text{T}$. Banwell and Farr conclude their article [135], p. 25, with the following sentences: “The authors consider that they have taken all precautions to eliminate causes tending to give a spurious effect greater than the probable error of observation quoted above. They would however be very hesitant in accepting the above final result as real. All that can be said definitely is that in such a field (20,000 oersted) the effect is less than 1 part in about 5×10^8 .” (For a discussion of this non-null result obtained by Banwell and Farr see our Appendix C.).

The influence of strong (inhomogeneous) electric fields on the propagation of light has been studied by J. Stark (Traunstein, later Eppenstein, Germany) in the years after World War II (For the role of Stark in fascist Germany see, e.g., [197], chap. 6, pp. 103-122, [198]). The motivation for such a study Stark derived from a light vortex model for photons (which, of course, implicitly entails the existence of nonlinearities in the corresponding electromagnetic theory); cf. [199], sec. 13, pp. 40-44. In his private laboratory he has conducted – among others – the following experiment ([145]; also see [199], sec. 14, pp. 44-50 (reprinted from [147]), [200]): A razor blade is positioned in a parallel trough cut out of a metal plate (perpendicular to the razor blade; cf. fig. 2 on p. 507 of [200]) at close distance. A narrow beam of polarized light passes along the razor blade in the space between blade and trough and consequently falls on a screen (photographic plate). The razor blade/metal plate

system is placed in a vacuum tube. The image produced by the light beam (mostly yellow light) is compared for the situation without any electric field applied and the situation where a strong electric field is applied between razor blade and metal plate. Stark estimates the strength of the electric field close to the razor blade to be 1 to 1.5×10^6 V/cm at maximum. He reports on the existence of a slight difference in the images for the cases with and without electric field applied once the electric field of the polarized light is perpendicular to the razor blade (cf. fig. 1 on p. 47 and fig. 2 on p. 48 of [199] and fig. 3 on p. 508 of [200]). For the case of the electric field of the polarized light parallel to the razor blade Stark reports a null result. The experiment of Stark has been repeated independently by J. Sperling (University of Kiel, Germany) [153, 156] who finds no effect whatsoever. For a discussion of other, related experiments of Stark see [148, 150, 151]. From out the modern point of view of quantum electrodynamics a null result does not come unexpected. Comparing the maximum value of the electric field given by Stark as 1 to 1.5×10^6 V/cm with the QED critical field strength $E_{\text{cr}} = \frac{c^3 m_e^2}{e\hbar} \sim 10^{16}$ V/cm (m_e is the electron mass) one immediately recognizes that the strong electric field used by Stark is too weak to give rise to any nonlinear quantum electrodynamic effects.

We conclude this subsection with the description of a somewhat speculative experimental proposal by H. Bauer (University of Kiel, Germany) made in 1931 [19]. The proposal starts with the theoretical observation of the existence of a source-free (Poynting) energy current $\mathbf{S} \sim \mathbf{E} \times \mathbf{B}$ in the simultaneous presence of (say, constant) magnetic (\mathbf{B}) and electric (\mathbf{E}) fields. Concerning the existence of such an energy current Bauer refers (see his footnote 3 on p. 38), among others, to Planck [201], second part, chap. 2, § 13, p. 26 (p. 34 of the English translation). It should be mentioned that the literature on this subject in later decades is controversial, however, Feynman, for example, expresses the same view as Planck [202], chap. 27, sec. 27-5, p. 27-8. Bauer notes that the existence of such an energy current (for constant cross-fields) had not (yet) been demonstrated experimentally. He then points out that a momentum current \mathbf{S}/c^2 is associated with the energy current \mathbf{S} . He then goes on to reason that if a non-vanishing cross section for photon-photon scattering would exist in nature (the constant magnetic and electric fields correspond to a coherent state of photons) one could light of frequency ν let propagate in (opposite) line with the momentum current \mathbf{S}/c^2 . The phenomenon of photon-photon scattering would then result in a (tiny) frequency change of the light photons which could be measured. He estimates that a frequency change related to a cross section of $2 \cdot 10^{-27}$ cm² should be observable. Bauer points out that a non-negative experimental result would entail a violation of the superposition principle (characteristic for the Maxwell theory), i.e., it would be related (effectively) to a nonlinear electromagnetic theory. Bauer further points out that a non-negative experimental result would show the physical reality of the Poynting energy current (in the constant cross-field situation) and at the same time prove the existence of the phenomenon of photon-photon scattering.

2.2.3 Propagation/scattering of photons in the Coulomb field of nuclei

While the experiments discussed further above have intentionally been devised to study the properties of light, the experiments referred to in this subsection have been performed historically with another objective, namely to advance the understanding of cosmic rays, to gain further insight into the nuclear structure of atoms, and to explore experimentally the predictions of (relativistic) quantum mechanics. In the early decades of the 20th century numerous experiments have been made to study the absorption and scattering of γ -rays emitted by radioactive materials by various targets. We will not review these experiments here, the interested reader is referred to [203, 204] (For a related historic account see [205]). Here, we are concerned with such γ -ray experiments performed by L. Meitner and collaborators (Hupfeld, Kösters; Kaiser Wilhelm Institute of Chemistry, Berlin, Germany) in the early 1930s [25, 206–211] (For a historic discussion of these experiments see [212]). In these γ -ray absorption and scattering experiments performed to explore the validity of the Klein-Nishina formula (one of the consequences of relativistic quantum mechanics) Meitner and collaborators found that for targets with large nuclear number (nuclear charge) the Klein-Nishina formula is not sufficient to correctly describe the experimental results. Apparently, besides the scattering of γ -rays off electrons (described by the Klein-Nishina formula) another physical process related to the atomic nuclei of the target material was also to be considered. Referring to the just discovered creation of positive electrons (positrons) by γ -rays in various materials, M. Delbrück (Kaiser Wilhelm Institute of Chemistry, Berlin, Germany) hypothesized in 1933 (in an addendum to an article by Lise Meitner – whose assistant he was by then – and H. Kösters)^[i], “. . . that it involves a *photoeffect* on one of the infinitely many electrons in states of negative energy, which according to Dirac’s theory fill the entire space with infinite density and would well be capable of such an absorptive process, by virtue of their interaction with the nucleus.” He then concludes: “Such a proposal has also the consequence that that these electrons of negative energy are capable of *scattering* γ -rays, and in fact *coherently*, analogous to the phenomenon of the *unshifted* Compton line.”

In appreciating the contribution by Delbrück one has to remind oneself that at the time of writing of this addendum the theory of quantum electrodynamics was still in its birth phase but Delbrück relied on the model picture of the Dirac sea to qualitatively describe an advanced quantum field theoretic process whose detailed nature Delbrück did not sketch. Today, to lowest order of QED perturbation theory contributions to Delbrück scattering – as it is now being called – can be depicted by Feynman diagrams as shown in Fig. 1.

Interestingly, in 1978 Delbrück has described his proposal and its further fate in an

^[i][25]: cf. our App. A, p. 38, p. 38; English transl. [212], Appendix, p. 135. The English translation given here slightly deviates from the English translation printed there in order to make the translation more adequate.

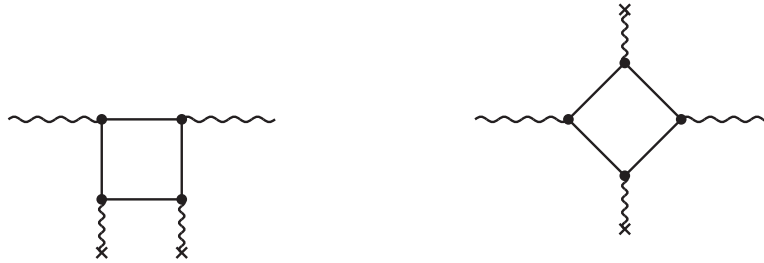


Figure 1: Typical (lowest order) Feynman diagrams contributing to Delbrück scattering (The wavy line ending in a cross depicts the Coulomb field of a nucleus.).

oral history interview of the California Institute of Technology Archives ([213], pp. 52-54 = Delbrück-45 - Delbrück-47) from which we quote in the following (with kind permission by the Caltech Archives):

“... One of the graduate students of Lise Meitner had studied the scattering by lead of gamma rays of ThC^{11} ; ThC^{11} is a gamma ray source with relatively hard gamma rays, as I recall, 2.6 million electron volts. If you scatter these gamma rays on lead, then, according to then current theory, you should find very little coherent scattering. Most of the scattered light should be Compton-scattered -- that means scattering where the electron acts as if it were a free electron. And after scattering you find, at right angles then, a Compton-scattered light quantum which is very much less energetic than the incoming one. This student, H. Kösters had found a scattered component which was much harder than the expected one. I put out the conjecture that this had something to do with the new theory of the electron that Dirac had proposed, according to which the negative energy states of an electron (with energies below minus mc^2) were all filled, and the electron never jumped from plus energy to minus energy because these were filled (because of Pauli’s exclusion principle). I made the conjecture that these negative energy electrons in the vicinity of the nucleus are not free electrons, but that their wavefunction was distorted by the nucleus of the atom and therefore that they could scatter. If they are free electrons then they wouldn’t scatter, but if they are disturbed by the field of the nucleus then there could be virtual transitions from minus to plus energy, and there would be corresponding scattering.

This problem is related to the problem of scattering of light by light. In the classical theory, two light beams just go right through each other and don’t interact, but in quantum electrodynamics if you take into account these negative energy electrons, then the first light beam polarizes the vacuum, and the second light beam then is scattered on

the first one. So I made a conjecture that these hard scattered rays should be due to this scattering of underground electrons. The fate of this conjecture was that it turned out that the scattered light, the scattered quanta observed by Kösters, were not due to that effect. Instead, they were due to the effect that the negative energy electrons actually absorbed a quantum, and thereby created a hole there, a positive electron. This positive electron then could recombine with some other electron and make annihilation radiation, and that is very much harder than the Compton-radiation. Actually that was an obvious implication that I had overlooked. And that came out very quickly. Nevertheless the effect that I predicted ought to be there also, and the question was how to calculate it, and I slaved on that and it turned out to be a nightmare to calculate that.¹²^[K.S.: orig. footn.] With the help of some advice by Hans Bethe I got so far as to predict that this effect should be proportional to the fourth power of the nuclear charge, Z^4 , and that's about all that I predicted; it was published in a short appendix, I think, to the paper by Kösters.¹²^[K.S.: orig. footn.]

That's where my contribution ended to this problem, and I never heard of it again until about 20 years later, in the fifties, when I was long since in biology. Somebody told me that there had been published two papers in Physical Review on "Delbrück scattering," by Bethe and some graduate students of his who had made some progress in calculating them.¹³^[K.S.: orig. footn.] So since then this name, "Delbrück scattering" exists, and if you ask theoretical physicists then I am known scurrilously for that little incident. I understand that the actual calculation of this effect, and experimental verification of it, still has been lingering on for the next 20 years after that, because it turned out to be just very, very difficult to calculate; also, in order to observe it you need to go to much higher energies -- I think the optimal energy is about 10 million electron volts rather than 2.7 -- and I think now it has been confirmed to exist. ...".

It remains to add that L. Meitner in 1934 [217] refers to a qualitative calculation

¹²[K.S.: In this context, W. Heisenberg reported in a letter of June 16, 1935 to W. Pauli: "Delbrück recently was here and reported about his fruitless attempts to calculate the coherent scattering. He certainly would be glad if he could do this work together with somebody else, e.g., Weisskopf (Sauter is now in Göttingen)." ([214], letter [374] of June 16, 1934, pp. 331-333, specifically p. 332: cf. our App. A, p. 38; English transl.: K.S.).

¹²[K.S.: orig. footn.] M. Delbrück, "Zusatz bei der Korrektur," in L. Meitner and H. Kösters, "Über die Streuung Kurzweiliger γ -Strahlen," Zeitschrift für Physik 84:137-144 (1933), 144. (K.S.: cf. [25])

¹³[K.S.: orig. footn.] F. Rohrlich and R. L. Gluckstern, "Forward Scattering of Light by a Coulomb Field," Physical Review 86:1-9 (1952); H. A. Bethe and F. Rohrlich, "Small Angle Scattering of Light by a Coulomb Field," Physical Review 86:10-16 (1952.) (K.S.: cf. [215, 216])

by Delbrück himself of the particular scattering process described by him in [25]^[k]. She quotes Delbrück as having calculated the angular distribution of the Delbrück scattering process and mentions that this calculation will be published in the near future. However, apparently this calculation never got published and also a preserved manuscript of it is not known. Related results have been published in 1937 by N. Kemmer and G. Ludwig (University of Zurich and ETH Zurich, Switzerland) [115]. Kemmer and Ludwig ([115], p. 184) give for the cross section q for the scattering of light of (long) wavelength λ ($\gg \hbar/mc$, $m = m_e$) off a nucleus with charge $Z|e|$ the formula (c_1, c_2 are certain unknown constants and θ is the scattering angle)

$$q = \left(\frac{e^2}{mc^2}\right)^6 \cdot \left(\frac{Z}{\lambda}\right)^4 \cdot [(c_1^2 + c_2^2)(1 + \cos^2 \theta) + 2c_1c_2 \cos \theta] \quad (1)$$

Related results have been published in 1937 by Akhiezer and Pomeranchuk [102] (cf. subsec. 3.2). As M. Delbrück in his Caltech Archives oral history interview recalls (see above quote) the further study of the Delbrück scattering process continued in the 1950's only.

2.3 Considerations related to extraterrestrial and astronomical observations

Since the earliest times of mankind, light has naturally played a prominent role in developing an understanding of the physical world we live in. It comes as no surprise that also the problem of photon-photon interactions (or, nonlinear electrodynamics, or possible violations of the superposition principle) has been approached by means of results of extraterrestrial and astronomical observations. In the period under consideration, three comments that belong to this line of research are known to us. One comment has been made by H. Ebert in 1887 [3] concerning the possible dependence of the speed of light on the intensity of the propagating beam, a second consideration on the subject of using the solar corona for obtaining limits on the violation of the (optical) superposition principle has been published in 1928 by S. I. Vavilov, and a third comment concerning a possible frequency dependence of the speed of light is due to F. Zwicky (California Institute of Technology, Pasadena, USA) in 1937 [123]. In the following, we will let Ebert and Zwicky speak for themselves by simply quoting from their articles while the somewhat longer discussion by Vavilov is being summarized only.

Let us first quote the relevant part of the paper by Ebert^[l] in which he makes

^[k]The memory of Max Delbrück in his above quoted interview apparently slightly mixes the course of events. His note [25] does not contain any calculation.

^[l][3], pp. 381-383: cf. our App. A, p. 38; English transl.: K.S.. To some extent the original German text exhibits a historic style used at the end of the 19th century, the present English translation does not deliberately attempt to imitate this historic style.

contact between his laboratory experiments (cf. subsection 2.2.1) and astronomical observations (an early example of astroparticle physics ...):

“At the end, I am allowing myself to apply the above result to some astrophysical questions.

Is the velocity of the propagation of light dependent on its intensity to some noticeable degree, beyond the circumstance that the phenomena in the sky occurring to us at the same moment belong to very different times in reality, the further complication would step in that these times even for equal spatial distance would be very different for the different objects. In view of the large differences in intensity that are being met here and in view of the large distances which the light rays have to pass before they can reach us, even small differences in the velocity of the propagation of light can make themselves noticeable to a large degree. For example, this should occur for physical double stars; here, we have got two sources of light that, in some rough approximation, are equally far away from us but whose intensity of light, in general however, considerably differs from each other. Despite this we find that - if we succeeded in calculating the trajectories of double stars - the two components indeed show up at the same time at corresponding points of their trajectories and together with their joint center of gravity always lie on a straight line. Right from this fact, we can also draw new support for the experimental result obtained by us.^[m]^[footn. K.S.] One example might incidentally show yet that the bound proved by me for the independence of the two quantities in question^[m]^[footn. K.S.] is completely sufficient for the astronomical practice.

According to calculations by Auwers and Peters, the companion of Sirius, calculated by Bessel and discovered by Clark, has an extraordinary large mass ($1/2$ to $2/3$ of the mass of Sirius itself). At the same time, it occurs to us as a star of about class 9 only, also compared with its main star, its brightness is a very small one, according to Schönfeld¹⁾^[K.S.: orig. footn.] appr. $1/1000$ of that of Sirius only. Further above, for rays of medium wavelength (for sodium light) it was found that for an attenuation of light from intensity 1 to intensity $1/33$ the velocity of the propagation of light does not change even by $1/500\,000$. Relying on this limit, i.e. assuming that for differences in brightness of 33:1 the velocity of propagation could differ just yet by this amount and that the latter would grow proportionally with the difference in intensity, in the present example, in each second the light of the companion would stay behind the light of the main star by $30 \times 0,6$ or 18 km. In light-time, the distance of the Sirius system amounts to about 30 years. Assuming it were precisely 30 years, it would take the light of the companion:

$$\frac{300\,000}{299\,982} \times 30 = 30,0018$$

years to reach us, i.e., of two simultaneously emanated light rays the one emitted by the companion would always arrive about 0.7 days later only than the one emitted by

^[m]K.S.: Cf. our subsec. 2.2.1.

^[n]K.S.: i.e., the velocity of light and the intensity of light.

¹⁾^[K.S.: orig. footn.] Schönfeld, Die dunklen Fixsternbegleiter. Mannheimer Verein für Naturkunde. 30. Jahresbericht. (K.S.: cf. [218])

Sirius itself. As, however, the period of revolution of both bodies around their joint center of gravity is 50 years, this difference in time and the difference in location corresponding to it can be neglected. The assumptions made, however, are very unfavourable ones; for all orbit determinations, we can disregard any dependence, existent yet perhaps, of the velocity of propagation on any intensity whose value lies below the limits established by the experiment.

Further, the obtained result is of relevance for applications of the Doppler principle where the relative velocities of the stars in the direction of the line of sight are determined from changes in the average refractivity of isolated spectral lines. Here, in the different cases very large differences in brightness exist and, consequently, for the applicability of this principle it is important to have shown directly that these differences in brightness do not also have an influence.”.

As described in subsection 2.1, Vavilov [11, 18] had performed in 1928 a laboratory experiment to attempt the direct (optical) observation of photon-photon scattering in vacuum. This experiment ended with a negative result: no photon-photon scattering has been observed. It should be noted that in 1928 the experiment had been based on a qualitative understanding of the quantum nature of light only, the later qualitative predictions of QED for the scattering of photons by photons were not yet made. To Vavilov it was clear that the superposition principle for electromagnetic radiation is fulfilled to a high degree, consequently, the experimental search for any signatures of photon-photon scattering is confronted with a tiny effect (if any at all). To Vavilov, a high radiation density was therefore the key for a possible observation of photon-photon scattering (Only the later QED calculations, see subsection 3.2, further clarified the situation: the size of the photon-photon scattering cross section is critically dependent on the photon energy.). In his article of 1928 Vavilov, therefore, also turned his attention to the sun with its large radiation density. From data concerning the solar corona he concluded that in any photon-photon scattering at most $1.8 \cdot 10^{-17}$ of the beam energy is being scattered ([11], § 2, p. 558, p. 237 of the reprint, pp. T-4 (= P-6) of the English translation; also see [18]). From this estimate he concludes that even if photon-photon scattering existed it could not be observed in any terrestrial experiment because the human eye would not be sensible enough to detect the low intensity of scattered photons (At that time, the human eye was the most sensitive photon detector in such a type of optical experiments, cf. e.g. [17], p. 777, last sentence.). Finally, noting that there was no satisfactory theory of the solar corona (in 1928) he then tried to explain (in a somewhat more hypothetical way) certain known features of the solar corona by means of photon-photon collisions (For a current treatment of the solar corona see, e.g., [219].).

Zwicky in 1937 [123] is concerned with a frequency dependence of the speed of light possibly arising within theories of nonlinear electrodynamics. He writes: “Certain effects have recently come to our knowledge which suggest that the differential equations governing the propagation of light through empty space are not

strictly linear. *Nonlinearity* of these equations results in a *dependence* of the *velocity of light on frequency*. One reason for the existence of slight deviations from the superposition principle of light lies in the potential possibility of the formation of pairs of positive and negative electrons by interacting photons. This interaction necessitates a generalization of Maxwell's field equations through the introduction of non-linear terms in the field strengths.⁵[K.S.: orig. footn.] As a result, light traveling through space which is free of matter but filled with radiation will have a velocity depending on its frequency. In addition similar effects arise from the gravitational interaction of light with light and matter. Although the effects to be expected are in all probability small the possibility of an experimental test may be kept in mind. An obvious way of investigating effects of the kind mentioned lies in the observation of light signals of different frequency which have traveled through space for a long time. If we knew of any signals which have started *simultaneously* from a very distant source the dependence of the velocity on frequency could perhaps be demonstrated by checking up on the times of arrival of these signals. A unique case to perform this test is afforded by the observation of distant nova outbursts. For such an outburst we may safely assume that photons in the various emission lines of, say, hydrogen have started out simultaneously on their long journey. We must therefore attempt to determine whether or not the intervals in which the different hydrogen lines flare up in the spectrum of a distant super-nova are zero or not. With the present telescopic equipment it is probably possible to find super-novae to distances as great as 10^8 light-years. With reasonable luck it should be possible to detect differences in the time of arrival of various emission lines amounting to as little as a few days. Observations of this kind will therefore enable us in the most favorable cases to determine the ratio of the velocity of violet light to that of red light traveling through internebular space with a relative accuracy of 10^{-10} .⁶

He then goes on to describe certain astronomical observations concerning novae in the Andromeda galaxy M31 which - at the time of writing - might be considered being related to a possible frequency dependence of the speed of light.

3 Theory

In classical electrodynamics the superposition principle holds true, consequently, direct interaction processes (without mediation by charged particles) of electromagnetic fields such as photon-photon scattering do not occur within this framework. Its theoretical description, Maxwell electrodynamics, is based on the following Lagrange density for the electromagnetic field

$$\mathcal{L}_0 = -\frac{1}{4\mu_0} F^{\mu\nu} F_{\mu\nu} = \frac{1}{2} \epsilon_0 (\mathbf{E}^2 - c^2 \mathbf{B}^2) = \frac{1}{2} \left(\epsilon_0 \mathbf{E}^2 - \frac{1}{\mu_0} \mathbf{B}^2 \right) \quad (2)$$

⁵[K.S.: orig. footn.] Euler and Kockel, *Naturwiss.*, **23**, 246 (1935). (K.S.: cf. [47])

where $F^{\mu\nu}$ is the electromagnetic field strength tensor and the velocity of light (squared) is given by $c^2 = 1/(\epsilon_0\mu_0)$ with ϵ_0, μ_0 being the dielectric permeability and the magnetic permittivity of the vacuum, respectively. A characteristic feature of the Maxwell theory is that the Lagrange density of the electromagnetic field is quadratic in the electric (\mathbf{E}) and magnetic (\mathbf{B}) fields. Electromagnetic theories which are to model direct interaction processes of electromagnetic fields have to be described by Lagrange densities which contain higher powers of the electromagnetic fields. The first theoretical study which considered Lagrange densities of the electromagnetic field of a more general form has been published by G. Mie (University of Greifswald, Germany) in 1912 [7]. However, Mie considered not only a dependence of the Lagrange density on the electric and magnetic fields themselves but also explicitly and separately on the electromagnetic potentials. In his famous review of the theory of general relativity [220] in 1920, W. Pauli (University of Munich, Germany) pointed out (§ 64, pp. 754-769, pp. 188-192 of the English translation) that the non-gauge invariant ansatz of Mie is physically not viable. The work of Mie does not contain any explicit reference to such processes as photon-photon scattering we are interested in in the present review but it has to be considered as the earliest theoretical approach in principle entailing such processes.

3.1 Born-Infeld electrodynamics

The following step in the further development of nonlinear Lagrangians for electromagnetism is closely related to a political-historic situation – the rise to power of the Nazi party in Germany in 1933. M. Born (University of Göttingen, Germany) describes in his autobiography [221] the situation he found himself in. After he had been dismissed from his chair at the University of Göttingen as a result of the fascist Law for the Restoration of the Career Civil Service [Gesetz über die Wiederherstellung des Berufsbeamtentums] of April 7, 1933 he immediately left Germany for Italy in May 1933. He writes about this time in Italy ([221], part 2, chapter IV, pp. 254-255): “I soon began to miss my accustomed work. But I had neither books nor periodicals. So I looked for a subject for which no literature was needed, something in quite a new line. I started from my old favourite problem, the electromagnetic mass of the electron, which I had treated in my thesis^{[o][footn. K.S.]} for admission as a lecturer. According to Coulomb’s law, the energy of a charged particle becomes infinite when the radius shrinks to nothing. One has therefore to assume that the electron has a finite size. But if it is a rigid sphere one gets into trouble with the theory of relativity because there, in general, rigidity does not exist. In my thesis (see Part 1, Chapter XI)^{[p][footn. K.S.]}, I had discovered that there are special movements for which rigidity can be defined, and I had obtained for these a definite expression for the self-energy (electromagnetic mass). But for arbitrary movements this was not possible. The only way out of this difficulty seemed to be the assump-

^[o]K.S.: i.e., habilitation thesis [222].

^[p]K.S.: Part 1, Chapter XI of [222].

tion that the ordinary Maxwellian theory of the electromagnetic field holds only approximately for dimensions large compared with the radius of the electron, while for smaller distances it should be replaced by another, more subtle theory. A quite general frame for modifying Maxwell's equations had been given, many years before, by Gustav Mie^[q]^[footn. K.S.]. I remembered these and tried to fill out this frame by special, plausible assumptions. But I was not successful though I spent many hours on my verandah pondering about it. At last I succeeded by abandoning Mie's formalism and inventing another one. The usual linear theory of the electromagnetic field was replaced by a non-linear one, in which point charges existed which carried a finite electrostatic energy.

I had no means (tables, etc.) to work it out numerically, and I remember the tension with which I waited for the letter from a colleague whom I had asked to evaluate the decisive elliptic integral. When it came I was very happy and proud^[r]^[footn. K.S.]; for I was filled with the intense desire to discover something fundamental to regain my self-confidence after the loss of my job in Göttingen, and to 'show the Germans what they had lost'. Alas, these ambitions were not fully satisfied. My non-linear field theory made some stir, but did not lead to the solution of the problem of the structure of elementary particles, although I spent a great deal of time and effort on it during the following years, together with a number of collaborators, in the first place the Pole Infeld. I shall return to this later. The so-called Born-Infeld theory was one of the first attempts at a non-linear field theory and worked perfectly in the 'classical' (non-quantum) domain, but failed in the quantum domain. Today one has a wide empirical knowledge about elementary particles, and it is clear that the electron cannot be treated separately. The most promising theory, that of Heisenberg, also uses non-linear field equations and follows thus the direction indicated by my work, but rests on quantum theory right from the beginning. In any case, this work helped me to overcome the bitter feelings produced by the loss of my position and my expulsion."

In his Letter to *Nature* [22] (followed by a full length paper [28] submitted for publication at about the same time, August 1933) M. Born proposed as a gauge-invariant nonlinear Lagrangian of electromagnetism the expression (b is some dimensionful constant; [28], p. 426, eq. (6.1))

$$\mathcal{L} = -\frac{b^2}{\mu_0} \sqrt{1 + \frac{\mathcal{F}}{b^2}}, \quad (3)$$

$$\mathcal{F} = \frac{1}{2} F^{\mu\nu} F_{\mu\nu},$$

which leads to a finite value of the self-energy of a point charge (in contrast to Maxwell electrodynamics) as shown by M. Born and L. Infeld (both at the Univer-

^[q]K.S.: [7].

^[r]K.S.: The first Letter of Max Born on this subject appeared in the journal *Nature* in August 1933 [22].

sity of Cambridge, UK) shortly thereafter [23]. Ya. I. Frenkel' (Physico-Technical Institute, Leningrad, USSR) immediately devoted two sections in volume 1 of the Russian edition (1934) of his teaching book on classical electrodynamics to this nonlinear electrodynamic theory by Born ([35], chap. X, § 11-12, pp. 407-422).

Once (arbitrary) nonlinear Lagrangians of the electromagnetic field are allowed the natural question arises by which principles the functional shape of the Lagrangian should be chosen. Born and Infeld formulated two general principles which should rule the choice of the Lagrangian: the *principle of the finite field* [24] (the corresponding full length paper is [30])/ *principle of finiteness* (“... a satisfactory theory should avoid letting physical quantities become infinite.” [30], § p. 427) and the postulate (principle) of the *invariance of action* (under space-time transformations, [30], § 2, p. 429)). Following earlier considerations by Eddington ([224], § 88, p. 206, eq. (88·4), § 97, p. 223, § 101, p. 232), Born and Infeld write down the expression (an additive constant is being omitted)

$$\mathcal{L} = -\frac{b^2}{\mu_0} \sqrt{1 + \frac{\mathcal{F}}{b^2} - \frac{\mathcal{G}^2}{b^4}}, \quad (4)$$

$$\mathcal{F} = \frac{1}{2} F^{\mu\nu} F_{\mu\nu}, \quad \mathcal{G} = \frac{1}{4} F^{\mu\nu} F^*_{\mu\nu} = \frac{1}{c} \mathbf{E} \mathbf{B},$$

as “... simplest Lagrangian satisfying the principle of general invariance” ([30], p. 432, below of eq. (2.26)). Contrasting eq. (4) with eq. (3) Born and Infeld state: “Which of these action principles is the right one can only be decided by their consequences.” ([30], p. 432, below of eq. (2.28)). A discussion of a large class of invariant Lagrangians in generalization of the eqs. (3), (4) has been given in 1935 by W. H. Erskine (Johns Hopkins University, Baltimore, USA) in his Ph.D. thesis [45, 46]. In the following years, the choice of the functional form of the Lagrangian has further been discussed in [66, 78–81, 86, 110–112, 118]. Infeld in his autobiography reports on his own view of the problem in late 1935 by saying: “... I recently discovered that Maxwell’s theory can be generalized in many different ways. This is not astonishing. But I no longer believe that the generalization presented by Born is the simplest. I don’t like the arbitrariness of the whole problem.” ([139], book two, sec. 13, p. 223 (p. 177 of the reprint # 1)). For the reader interested in science history we would like to mention that both the autobiographies of Born [221] and Infeld [139] contain much interesting material which provides the reader with a unique insight into the development of the Born-Infeld theory.

The introduction of nonlinear Lagrangians of the electromagnetic field has resulted in a number of directions of thought whose significance is not limited to the particular Lagrangians considered by Born and Infeld. Some of these are:

- The nonlinear electromagnetic Lagrangians (3), (4) contain a dimensionful constant b which sets the scale for the nonlinearity and, consequently, for the

deviation of phenomena from the predictions of (linear) Maxwell electrodynamics. Considerations concerning the value of b have been given by Born and Infeld [30], § 8, p. 446, eq. (8.8), and Born and E. Schrödinger (University of Oxford, UK)[43].

- One of the physical consequences of choosing a nonlinear Lagrangian of the electromagnetic field consists in modifications of the Coulomb law (potential) in the vicinity of a charged particle. Resulting effects in spectroscopic problems have been discussed for the first time by G. Heller and L. Motz (Columbia University, New York, USA) [37] right in 1934 concluding, however, that these are “barely observable” ([37], p. 505) in the problem under consideration (fine structure of the Balmer series for hydrogen). Later, J. Meixner (University of Gießen, Germany) [54], Z. Chrapływyj (Jan Kazimierz University, Lvov, Poland) [73, 107], and B. S. R. Madhava Rao (Indian Institute of Science, Bangalore, India) [116] have further extended these investigations drawing the same final conclusion, however. A. Bramley (Bartol Research Foundation, Swarthmore, USA) [69] explored possible consequences of Born-Infeld electrodynamics on the scattering of charged particles off each other.
- Nonlinear electromagnetic theories exhibit a rich field-theoretic structure differing from that of standard Maxwell electrodynamics. Therefore, formal field-theoretic studies to explore the mathematics related to nonlinear electromagnetic Lagrangians are necessary. Besides Born and Infeld themselves [28, 30] a group of other authors has studied formal aspects of nonlinear electrodynamics. A number of investigations are dealing with the description of the dynamics and the status of charged particles in nonlinear electrodynamics [31, 34, 44, 48, 71, 72, 92, 93, 98, 106–108, 129, 131, 134, 142]. Others studied the introduction of complex field variables into the formalism [61, 65, 83, 88, 121, 122], investigated solutions of the field equations [57, 58, 89, 117, 129, 133, 144], and explored further questions [62, 68, 75, 85, 87, 90, 99, 117, 124, 126, 130].
- The quantization of the nonlinear electromagnetic theory has received some attention (in the time period under consideration quantum electrodynamics was still in its infancy). Here, besides the studies by Born and Infeld [29, 32, 33, 42, 113] few further investigations exist [53, 59, 91, 94, 119, 143].
- Born and Infeld have considered the electromagnetic theory in Minkowski space. However, in the time period under consideration in the present review the problem of the unification of gravitation and electromagnetism has been explored widely. In the context of the Born-Infeld theory, this problem has been considered by B. Hoffmann (University of Rochester, USA) [38], [51] (this is the full length paper related to the Letter [38]), [49, 50] and other authors [40, 127, 130, 146, 149].

In the following we would like to discuss in somewhat greater length three such further subjects that are more closely related to the phenomenon of photon-photon

scattering.

1. The scattering of light by light

The first comment on the scattering of light by light within the framework of Born-Infeld theory can be found in the classical article by Euler and Kockel [47] on photon-photon scattering in QED where they point out that the lowest order terms in the QED (effective) Lagrangian of the electromagnetic field responsible for this process are fairly similar to those in the Born-Infeld Lagrangian (The most obvious difference lies in the numerical value of some coefficients involved. For the view of W. Pauli in this respect cf. our App. F.).

In 1936, a first thorough analysis within (classical) nonlinear electrodynamics of the interaction of two light waves is given in Chap. II, § 5 (pp. 59-66, pp. T-59 - T-66 (= P-63 - P-70) of the English translation) of the candidates (Ph.D.) thesis of A. A. Smirnov (Ural Physico-Technical Institute, Sverdlovsk, USSR) [96]. Smirnov relies in his analysis on the action (3) initially chosen by Born [28] which only contains the invariant \mathcal{F} of the electromagnetic field. The analysis is performed to leading nontrivial order in the constant b (the critical field strength). In principle, this kind of analysis is also applicable to the Euler-Kockel-Heisenberg Lagrangian (which however depends on both of the field invariants \mathcal{F} and \mathcal{G}). For counterpropagating electromagnetic waves (for the choice of polarization see the original thesis [96]) he finds as main results a change in the phase velocities and the emergence of small wave components with significantly different frequencies compared with the initial waves (e.g., for initial waves of the same frequency ω wave components with triple frequency 3ω emerge, i.e., higher-harmonics generation is found). The above analysis of Smirnov is published in 1940/41 [136, 140] only in a slightly generalized form (cf. the footnotes on p. 449 of [136] and on p. 48 of [140]).

In 1942, as part of a larger study, Schrödinger (Dublin Institute for Advanced Studies, Ireland) also published an approximate analysis of the interaction of two light waves [141], Part I, Sec. 4, pp. 85-88 (pp. 317-320 in [270]) within the framework of the Born-Infeld theory (Schrödinger relies on the form of the action (4)). He also finds as main result, as Smirnov did, a change in the phase velocities of the two waves. Schrödinger also studied the interaction of three light waves [141], Part I, Sec. 5, pp. 88-92 (reprint [270], pp. 320-324). Somewhat later, in 1943, Schrödinger also found an exact two-wave solution of the equations of motion of Born-Infeld theory [144].

It should also be mentioned that in late 1936 an erroneous analysis of the interaction of two light waves in Born-Infeld theory has been published by C. D. Thomas (University of Chicago, USA) [97]. He assumed unchanged phase velocities in his Ansatz for solving the wave equation (e.g., cf. [97], p. 1048, eq. (16)). This incorrect assumption, however, leads to (physically not acceptable) wave solutions whose

amplitude is linearly growing in time (cf. [97], p. 1048, eqs. (14), (14')) invalidating hereby the further analysis. The papers of Smirnov and Schrödinger both contain comments on the danger of such unphysical solutions (Smirnov: [96] Chap. II, § 2, pp. 35-37, pp. T-35 - T-37 (= P-39 - P-41) of the English translation, [136], p. 449, [140], pp. 47-48; Schrödinger: [141], Part I, Sec. 4, p. 87 (reprint [270], p. 319), around eq. (4.10)).

Finally, in 1943 J. McConnell (Dublin Institute for Advanced Studies, Ireland) published an analysis of photon-photon scattering in the framework of the Born-Infeld theory [143]. Again, the analysis is performed to leading nontrivial order in the constant b (the critical field strength) and can, therefore, be compared to the description of photon-photon scattering in the framework of the Euler-Kockel-Heisenberg Lagrangian [47, 74, 76] of QED. The quantization is performed on the level of an effective field theory technique (phrasing it in modern field theoretic terms) and the resulting cross section for photon-photon scattering is compared with the analogous QED result ([143], Sec. 4, pp. 170-171). McConnell finds that the angular dependence of the differential cross section for photon-photon scattering and the dependence on the photon frequency are the same to lowest nontrivial order in (quantized) Born-Infeld theory and QED.

2. The scattering of light by electromagnetic background fields

In the time period under review, the consideration of the scattering of light by electromagnetic background fields has been performed for two different situations: for constant homogeneous electric and magnetic fields and for the presence of a Coulomb field.

A first short note studying the case of a constant homogeneous electric background field is published by S. P. Shubin (Ural Physico-Technical Institute, Sverdlovsk, USSR) and Smirnov in 1936 [95]. Details of the calculation are contained in the candidates (Ph.D.) thesis of Smirnov ([96], Chap. II, § 2, pp. 33-48, pp. T-33 - T-48 (= P-37 - P-52) of the English translation) which also comprises an analogous investigation of the case of a magnetic background field (Chap. II, § 4, pp. 55-58, pp. T-55 - T-58 (= P-59 - P-62) of the English translation). Shubin and Smirnov primarily find for a weak test wave that to leading order (in the critical field strength b) the electric background field causes a change in the phase velocity of the test wave, in dependence on the direction of its propagation and its polarization. They compare the situation found for the Lagrangian (3) to the birefringence found in an uniaxial crystal (also see [120], footnote * on p. 132 of the English version; this footnote does not exist in the Russian version). In his thesis ([96], Chap. II, § 3, pp. 48-55, pp. T-48 - T-55 (= P-52 - P-59) of the English translation.), Smirnov extends the analysis to the next to leading order in b . As additional effects of the electric background field he obtains higher harmonics generation in the forward and backward directions of the test wave and also a small component scattered backwards with the

frequency of the test wave itself. A couple of years later, in 1942 Schrödinger [141], as one part of a broad analysis of the consequences of the Born-Infeld Lagrangian (4), also observes that an electric background field exerts a refractive effect on a weak test wave (p. 102; p. 334 of the reprint). In accordance with general insight obtained decades later [225, 226], in difference to Shubin and Smirnov who rely on the Lagrangian (3) he finds no birefringence.

Within nonlinear electrodynamics, the first study of the situation that corresponds to Delbrück scattering in QED, i.e., the scattering of light by a Coulomb field, has been published in 1937 by Shubin and Smirnov [120]. For a fairly general class of nonlinear electrodynamic Lagrangians, they analyze the scattering of light from a point charge and find the polarization averaged differential cross section (in a certain approximation). Then, they specify their result for the choice of the Born-Infeld Lagrangian (4). Furthermore, they also include a discussion of their results on a level where comparison with the corresponding results for the Euler-Kockel-Heisenberg Lagrangian is possible. In 1940, Smirnov publishes a follow-up paper [137] where instead of the Born-Infeld Lagrangian the Lagrangian proposed by Hoffmann and Infeld [111] is being used. The work by Shubin and Smirnov was followed in 1938 by a paper by S.I. Tomonaga and M. Kobayasi (both at RIKEN – Institute of Physical and Chemical Research, Tokyo, Japan) who along analogous lines analyzed the low-frequency scattering of light by a point charge in Born-Infeld theory. A couple of years later, in a comprehensive study Schrödinger [141] takes up the subject (Part II, pp. 100-116; pp. 332-348 of the reprint). In part he agrees with the results of Shubin/Smirnov and Tomonaga/Kobayasi for the cross section of the scattering of light from a charged point charge, in part he finds further terms (cf. eq. (10,10) on p. 109; p. 341 of the reprint).

3. The splitting of photons in electromagnetic background fields

Tomonaga and Kobayasi in their paper [132] also considered for the first time within Born-Infeld theory the process of photon splitting, i.e., the splitting of one incoming photon in the Coulomb field of a point charge into two outgoing photons. In the case of QED, the same process had been mentioned before by E. J. Williams (University of Copenhagen, Denmark) in 1935 [63], § 10, pp. 47-49 (cf. the subsec. 3.2). Tomonaga and Kobayasi calculate the differential cross section for the photon splitting process in some low-frequency approximation.

4. The Stefan-Boltzmann law

L. Rosenfeld and E. E. Witmer (University of Göttingen, Germany) [12] have pointed out in 1928 that interactions between photons will lead to changes in the characteristics of black body radiation. Their discussion amounts to a qualitative consideration without specifying details of the interactions among the photons being part of the cavity radiation. They only mention (p. 521) that possibly correction terms to the

Maxwell equations could describe such interactions. Born-Infeld theory just specifies such correction terms to the Maxwell equations. Consequently, in 1936 B. Kwal and J. Solomon (France) [84] for the first time quantify the leading correction to the Stefan-Boltzmann law for the energy density u of black body radiation. They find (σ is some constant):

$$u = \sigma T^4 \left(1 + \frac{14\pi\sigma T^4}{b^2} \right). \quad (5)$$

Some time later, both authors present a derivation of the Stefan-Boltzmann law within a fairly large class of nonlinear electrodynamic theories [125]. Equations analogous to eq. (5) have later also been obtained by E. Milkutat (Berlin, Germany) [128] and Schrödinger [141], p. 100, eq. (7, 18) (p. 332 of the reprint [270]).

The early development of Born-Infeld electrodynamics in general has been described by few reviews. The most comprehensive one is the review written by Max Born himself in 1937 [103]. Less comprehensive are conference expositions of 1935 by Born [41] and of 1937 by Chrapływyj [109]. Finally, it also seems worth mentioning sections on Born-Infeld theory in the monographs by Frenkel' [35] (гл. [gl.]/[chap.] X, §11, §12), Sommerfeld [152] (Teil [part] IV, §37), and Ivanenko/Sokolov [154] (§32).

We conclude this section with two statements (dating from different times) by Albert Einstein and Max Born himself concerning Born-Infeld electrodynamics. In a private letter of March 22, 1934, Albert Einstein writes to Max Born ([227], letter 69, pp. 169/170, for the original German text see our App. A, p. 40; here we quote the English translation [228], p. 122.): “I am greatly interested in your attempt to attack the quantum problem of the field from a new angle, but I am not exactly convinced. I still believe that the probability interpretation does not represent a practicable possibility for the relativistic generalisation, in spite of its great success. Nor has the reasoning for the choice of a Hamiltonian function for the electromagnetic field, by analogy with the special theory of relativity, convinced me. I am afraid that none of us will live to see the solution of these difficult problems.”. Max Born comments this letter many years later (in 1969) by the following words ([227], pp. 170/171, for the original German text see our App. A, p. 40; here we quote the English translation [228], pp. 122/123.): “Einstein’s objections to my ideas were twofold. The first was based on his rejection of the probability of quantum mechanics. This concerns a matter of principle. It did not really apply to the theory devised by Infeld and myself, because we ourselves did not in fact manage to make it fit in with quantum mechanics; he judged our efforts in this direction to be wrong in principle. Einstein’s second objection concerned our original classical field theory, which was complete in itself and free from inconsistencies. It was based on the following analogy: in the special theory of relativity the kinetic energy of a particle, which in classical mechanics is proportional to the square of its velocity, is represented by a rather complicated expression; for velocities which are small compared

with that of light it tends to the classical expression, but deviates from it when the velocity approaches that of light. In Maxwell’s electrodynamics the energy density is a quadratic expression containing the field intensity. I replaced this with a general expression which approximates to the classical expression whenever the strength of the field is small compared with a certain field intensity, but diverges from it when this is not the case. From this it followed automatically that the total energy of the field of a point charge is finite, while it becomes infinite in the Maxwellian field. The absolute field has to be regarded as a new natural constant. Einstein did not find this analogical construction convincing. Infeld and I found it attractive for a long time. We abandoned the theory for completely different reasons, namely, because we did not succeed in reconciling it with the principles of the quantum field theory. In any case this constituted the first attempt to overcome the difficulties of microphysics by means of a non-linear theory. Heisenberg’s theory of elementary particles, which is much talked about today, is also non-linear. But I am guessing.”

3.2 Quantum electrodynamics

As we have discussed in the Introduction (section 1), in the late 1920’s among physicists the idea developed that the emerging quantum theory should also allow and describe the scattering of photons by photons. However, the physical mechanism for such scattering events initially remained unclear. With the proposal by P. A. M. Dirac of the equation named after him (1928), the discovery of the positron (C. D. Anderson, 1932), and the first steps towards the theory of quantum electrodynamics elements of a possible explanation became available. O. Halpern (New York University, USA) [26] proposed in late 1933 in a short, qualitative note that the occurrence of virtual electron-positron pairs could be identified as the physical mechanism by means of which photon-photon scattering occurs (a more elaborate quantitative discussion announced by the author at the end of the note seems not to have emerged). The note of Halpern had been preceded by the discussion of two-photon production in “electron-proton” annihilation^[s] by Dirac [230], Oppenheimer [231], Tamm [232], the process of electron-positron pair creation by a photon in the field of an atomic nucleus by Oppenheimer and Plesset [233] (also see, published somewhat later, Heitler and Sauter [234], Bethe and Heitler [235], Nishina, Tomonaga, and Sakata [236, 237], Racah [238]), and the Breit-Wheeler process [239, 240] of electron-positron creation in two-photon scattering. Furthermore, also P. Debye is credited by W. Heisenberg to have mentioned similar ideas as Halpern in a private discussion with him^[t]. In early 1935, D. D. Ivanenko (Physico-Technical Institute, Leningrad, USSR) [52], with reference to the article [36] (containing references to Halpern [26] and Debye), also discussed in a short qualitative note the possible role

^[s]This process of “electron-proton” annihilation found its proper re-interpretation as electron-positron pair annihilation after the discovery of the positron in 1932 only.

^[t][36], p. 228, footnote 2 [also cf. [47], p. 246, footnote 5, [74], p. 398, footnote 3 (footnote 2 in the separate Thesis print)]

of the occurrence of virtual electron-photon pairs for photon-photon scattering. He points out that the existence of photon-photon scattering entails the violation of the superposition principle [characteristic for the (linear) Maxwell theory of electromagnetism], i.e., the phenomenon of photon-photon scattering is characteristic for a nonlinear electromagnetic theory. Consequently, as Ivanenko notes, the Dirac theory leads to some nonlinear electromagnetic theory which needs to be identified. Somewhat formal attempts to link the Dirac equation with nonlinear electrodynamics, specifically with the theory proposed by Born, have been published in 1935 by K. V. Nikolskiĭ (Steklov Mathematical Institute, Moscow, USSR) [55, 56].

A first answer to the task described by Ivanenko is given almost simultaneously in time: A completely new level in the discussion of photon-photon scattering is reached with the appearance in print in spring 1935 of a short article by H. Euler and B. Kockel (both doctoral students of Heisenberg at the University of Leipzig, Germany; for some reminiscences of W. Heisenberg concerning this research see our Appendix E) [47]. The article marks the transition from qualitative considerations concerning the phenomenon of photon-photon scattering to detailed quantitative calculations. The short article is followed in 1936 by the doctoral thesis of H. Euler [74]^[u] which contains a comprehensive exposition of the calculation used by Euler and Kockel to arrive at the results presented in [47] (For a detailed discussion of certain aspects of this Thesis see sec. 2.1, pp. 23-28 of [242]). Euler and Kockel determined the leading perturbative correction (for small field strengths and photon frequencies well below the electron-positron pair production threshold) to the Lagrange density \mathcal{L}_0 of the Maxwell field. They find (cf. eq. (10,6) on p. 444 of [74], written here in SI units):

$$\mathcal{L} = \mathcal{L}_0 + \frac{\alpha^2}{360} \frac{\epsilon_0^2 c^3 \lambda_e^4}{\hbar} \left[4 (F^{\mu\nu} F_{\mu\nu})^2 + 7 (F^{\mu\nu} F_{\mu\nu}^*)^2 \right] \quad (6)$$

$$= \mathcal{L}_0 + \frac{2\alpha^2}{45} \frac{\epsilon_0^2 \lambda_e^4}{\hbar c} \left[(\mathbf{E}^2 - c^2 \mathbf{B}^2)^2 + 7c^2 (\mathbf{E}\mathbf{B})^2 \right] \quad (7)$$

$$= \mathcal{L}_0 + \frac{2\alpha^2}{45} \frac{\lambda_e^4}{\hbar c} \left[4 \mathcal{L}_0^2 + \frac{7}{\mu_0^2} (\mathbf{E}\mathbf{B})^2 \right] \quad (8)$$

with the free field Lagrange density

$$\mathcal{L}_0 = -\frac{1}{4\mu_0} F^{\mu\nu} F_{\mu\nu} = \frac{1}{2} \epsilon_0 (\mathbf{E}^2 - c^2 \mathbf{B}^2) = \frac{1}{2} \left(\epsilon_0 \mathbf{E}^2 - \frac{1}{\mu_0} \mathbf{B}^2 \right). \quad (9)$$

The used symbols are: α is the fine structure constant, $\lambda_e = \hbar/(m_e c)$ is the (reduced) Compton wavelength of the electron with mass m_e , the velocity of light (squared)

^[u]In his thesis review (University of Leipzig Archive, Philosophical Faculty, Prom. 769, reprinted in [241], pp. 125/126), Heisenberg credits Debye with having initiated this thesis research by posing him a question (quoted here after [241], p. 126: cf. our App. A, p. 41; English transl.: K.S.): “The subject of the present work originates from a question posed to me by colleague Debye.”

is given by $c^2 = 1/(\epsilon_0\mu_0)$ with ϵ_0 , μ_0 being the dielectric permeability and the magnetic permittivity of the vacuum, respectively, $F_{\mu\nu}^* = \epsilon_{\mu\nu\alpha\beta}F^{\alpha\beta}/2$ is the dual of the electromagnetic field strength tensor $F^{\mu\nu}$. Using the relations given in the eqs. (D.4), (D.5) of Appendix D, one can write eq. (8) the following way

$$\mathcal{L} = \mathcal{L}_0 + \frac{2\alpha^2}{45} \frac{\lambda_e^4}{\hbar c} \left[-10 \mathcal{L}_0^2 + \frac{7}{4} T^{\mu\nu} T_{\mu\nu} \right] \quad (10)$$

$$= \mathcal{L}_0 + \frac{2\alpha^2}{45} \frac{\lambda_e^4}{\hbar c} \left[-10 \mathcal{L}_0^2 + 7 \left((T_{00})^2 - \frac{1}{c^2} \mathbf{S}^2 \right) \right] \quad (11)$$

where $T^{\mu\nu}$ (eq. (D.2)) is the stress-energy-momentum tensor of the free electromagnetic field, and the Poynting vector is given by

$$\mathbf{S} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B} . \quad (12)$$

The found (Euler-Kockel-Heisenberg) Lagrangian (EKH Lagrangian) is a nonlinear Lagrangian for the electromagnetic field which leads to nonlinear corrections to the classical Maxwell equations. The resulting (effective) Maxwell equations do not respect the superposition principle and describe nonlinear electromagnetic phenomena such as photon-photon scattering. One can recognize from eq. (11) that the term quadratic in the Poynting vector provides us with an interaction term between electromagnetic (photon) energy currents which is relevant for the experimental proposal by Bauer [19] discussed at the end of subsec. 2.2.2. Euler and Kockel also give for the first time a quantitative estimate for the cross section σ of photon-photon scattering. They find (for photons of frequency $\hbar\omega \ll m_e c^2$):

$$\sigma \sim \alpha^4 \lambda_e^8 \left(\frac{\omega}{c} \right)^6 \quad (13)$$

entailing a size of the cross section of 10^{-30} cm^2 for γ -rays and of 10^{-70} cm^2 for visible light ([47], bottom of p. 247, [74], p. 446, eq. (10,10))^[v]. These cross sections are fairly small and Euler immediately points out ([74], p. 446, below of eq. (10,10)) that this will make it difficult to experimentally prove the phenomenon of

^[v]In a letter of June 17, 1934 quoted here from [214], p. 331 (cf. our App. A, p. 41; English transl.: K.S.), W. Heisenberg mentions to N. Bohr that: “Debye came up with the idea that the solar corona originates from this scattering of light; the above value $[(e^2/\hbar c)^4(\hbar/mc)^2]$ for the cross section] would excellently fit this thesis. However, as already said, one still has to see whether all calculations are correct.” In a letter one day earlier ([214], letter [374] of June 16, 1934, pp. 331-333, specifically p. 332: cf. our App. A, p. 41; English transl.: K.S.), W. Heisenberg also wrote to W. Pauli: “This value seems to fit well to the idea of Debye that the solar corona emerges through this scattering of light by light.” S. I. Vavilov had discussed the possible role of the scattering of light by light for the emergence of the solar corona in his article [11] in 1928 (cf. subsec. 2.3) which is the written version of a talk delivered by him at the VI Congress of Russian Physicists in the same year (cf. [243], p. 47, item 80). P. Debye has been a participant to this congress (cf., e.g., [244], chap. 6, p. 226, English translation: chap. 4, p. 140). It is well possible that he had listened to the talk of S. I. Vavilov.

photon-photon scattering. This is a comment proving its significance even today after 80 years. Furthermore, the cross section estimate of Euler and Kockel explains the negative results of all experiments performed earlier (discussed in subsec. 2.1) to directly detect photon-photon scattering.

Roughly one year after the article by Euler and Kockel [47] an article by Heisenberg and Euler [76] appeared in print which considerably extended the result obtained by the former. While Euler and Kockel limited the perturbative calculation of the effective Maxwell Lagrangian to sufficiently small electromagnetic fields, Heisenberg and Euler solved the Dirac equation for constant, arbitrarily strong, parallel magnetic and electric fields and calculated on the basis of this information the effective Maxwell Lagrangian. This (in modern terms: 1-loop) effective Maxwell (Euler-Heisenberg) Lagrangian for constant electromagnetic fields together with its weak-field limit, the EKH Lagrangian, represents a milestone in the history of quantum field theory.

An independent confirmation of the results obtained by Euler and Kockel came in 1936 with a short note by N. Kemmer and V. F. Weisskopf (University of Zurich and ETH Zurich, Switzerland) [82]. Some aspects of this work, which cannot easily be read from this short note, are pointed out by V. F. Weisskopf in an oral history interview in 1965^[w]: “We connected the scattering of light by light with the Delbrück scattering. Today it’s a triviality; one light quantum is replaced by the Coulomb field^{[x]^[footn. K.S.], but at that time it was not so trivial. . . Euler and Kockel at that time, under Heisenberg, calculated the scattering of light by light, but had to do a lot of subtracting because there were a great many terms that were infinite. They did this in the usual clever way and got the result. And Kemmer and I showed that you can do the calculation without raking any subtractions, because you can show that it is equivalent to the Delbrück scattering, replacing one light quantum by the Coulomb field, and the Delbrück scattering doesn’t diverge.” The same year, a long paper by Weisskopf [100] presented a more efficient and improved re-derivation of the Euler-Heisenberg Lagrangian (For some historic recollections by V. F. Weisskopf also concerning this article see our Appendix G.). In [100], Weisskopf in principle follows the path taken by Heisenberg and Euler [76] but solves the Dirac equation for a constant magnetic field accompanied by a parallel, spatially periodic electric field. While Heisenberg and Euler, considering a constant electric field, had to deal with the Klein paradox (any spatially constant electric field creates electron-positron pairs) Weisskopf was able to sail around this difficulty by considering a sufficiently weak, spatially periodic electric field for which no electron-positron pair creation occurs. The result of his calculation confirmed the expression obtained by Heisenberg}

^[w]Cf. our Appendix G (quotation with kind permission of the American Institute of Physics), for some related historic recollections by Kemmer see our Appendix H.

^[x]K. S.: More precisely, they consider for the scattering electric field \mathbf{E} the condition $|\text{grad } \mathbf{E}| \ll |\mathbf{E}| mc/h$ (weakly varying fields at a length scale of the electron Compton wavelength) which in the strict sense is not fulfilled for the Coulomb field: in a region close to the center of the nucleus.

and Euler for the effective Maxwell (Euler-Heisenberg) Lagrangian.

The theoretical study of photon-photon scattering was also in the focus of research interests elsewhere: L. D. Landau (Ukrainian Physico-Technical Institute, Kharkov, USSR) handed the task of studying certain aspects of photon-photon scattering to his doctoral student A. I. Akhiezer. As a first result a short note by Akhiezer, Landau, and I. Ya. Pomeranchuk (Ukrainian Physico-Technical Institute, Kharkov, USSR) appeared [64] treating for the photon-photon scattering cross section the high-frequency case $\hbar\omega \gg m_e c^2$. They found:

$$\sigma \sim \alpha^4 \left(\frac{c}{\omega}\right)^2 \quad (14)$$

noting that the proportionality factor is difficult to compute (In the low frequency case $\hbar\omega \ll m_e c^2$ studied by Euler and Kockel [47] the proportionality factor can be found from the EKH Lagrangian.). The result by Akhiezer, Landau, and Pomeranchuk showed that the cross section σ for photon-photon scattering must have “a maximum value in a region $\hbar\omega \sim m_e c^2$ ” ($m = m_e$) [64]. The kand. diss. (Ph.D. Thesis) research of A. I. Akhiezer giving the details of the calculation leading to eq. (14) is finally published in 1937 [101] (For historic recollections concerning the thesis research of A. I. Akhiezer see our Appendices I, J.). It should be mentioned that in 1935 also W. Pauli (University of Zurich, Switzerland) spent some time attacking the problem of high-frequency photon-photon scattering^[y]. However, the calculation proved to be difficult and in a letter of December 5, 1935^[z] Pauli informed Weisskopf: “Presently, the “Euler-Kockel” problem for short waves looks somewhat bleak to me.” and in a later letter of January 20, 1936^[aa] Pauli told Weisskopf: “After a discussion with Oppenheimer, I have now definitely given up as too complicated the problem of the scattering of light by light for short waves.” A short time later, the *Nature* article by Akhiezer, Landau, and Pomeranchuk [64] appeared in print.

Besides the fundamental nonlinear quantum-electrodynamic process of photon-photon scattering related phenomena have found attention at about the same time. As discussed in subsec. 2.2.3, in 1933 Delbrück [25] had qualitatively considered the interaction of photons with the Coulomb field of nuclei via their impact on the surrounding QED vacuum^[bb]. However, the cross section calculations related to this process Delbrück attempted in the time thereafter proved to be extremely difficult (cf. footnote [j] on p. 17). Weisskopf then independently took a look at the

^[y]See his letter [421a], [245], pp. 769-771 (specifically p. 770) of September 27, 1935 to Weisskopf, the corresponding section is quoted in our Appendix F.

^[z]Reprinted as letter [423b] in [245], pp. 777/778, specifically p. 778: cf. our App. A, p. 41; English transl.: K.S..

^[aa]Reprinted as letter [425c] in [245], pp. 780-782, specifically p. 782: cf. our App. A, p. 41; English transl.: K.S..

^[bb]For another discussion of the articles to be considered in this paragraph on Delbrück scattering see [246], subsec. 3.1, pp. 84-87.

problem, but as W. Pauli reported to W. Heisenberg in June 1935^[cc]: “Weisskopf is on the Delbrück problem and the problems of subtraction physics occurring there are getting not very nice.” Finally, in 1936 the joint work of Weisskopf and Kemmer paid off and as a first result – as already mentioned above – they established a connection between the scattering of light by light in the low-frequency domain and Delbrück scattering (understood here in a somewhat generalised sense as scattering of photons from a sufficiently slowly varying electric field) and confirmed this way the expression for the EKH Lagrangian [82] (also cf. our Appendices G, H). Details of the calculation were given by Kemmer in 1937 in [114]^[dd]. A short follow-up article by Kemmer and Ludwig [115] explored the calculational aspect that occur if the assumption of a sufficiently slowly varying electric field is given up and the Coulomb field is considered instead. For this case, they derived qualitatively an expression for the low-frequency (differential) cross section [cf. eq. (1) at the end of subsec. 2.2.3] which, however, contained two unknown constants. Simultaneously with Kemmer and Ludwig, Akhiezer and Pomeranchuk had considered Delbrück scattering [102]. They obtained in the low- and high-frequency limits ($\hbar\omega \ll m_e c^2$ and $\hbar\omega \gg m_e c^2$, respectively; ω is the photon frequency) expressions for the total cross section whose size however remained undetermined up to a constant. Specifically, they found for $\hbar\omega \ll m_e c^2$ [in accordance with the above eq. (1) on page 18]:

$$\sigma = b Z^4 \left(\frac{e^2}{m_e c^2} \right)^6 \left(\frac{\omega}{c} \right)^4 \quad (15)$$

and for $\hbar\omega \gg m_e c^2$ (the absorptive contribution of real electron-positron pair creation is not included):

$$\sigma = a \alpha^2 Z^4 \frac{c^2}{\omega^2} \ln \frac{\hbar\omega}{m_e c^2} \quad (16)$$

where a and b are unknown constants. Akhiezer and Pomeranchuk conclude again^[ee]: “The effective cross section has a maximum at $\hbar\omega \sim mc^2$.” ($m = m_e$).

In the period under consideration, besides photon-photon scattering and Delbrück scattering the possible phenomenon of splitting of photons has also been discussed. Halpern [26] had mentioned in 1933 photon splitting as a process conceivable in principle within quantum electrodynamics. Following Halpern, W. Heitler (University of Bristol, UK) in 1936 in his book also mentioned this possibility ([77], 1.

^[cc][214], letter [412] of June 15, 1935, pp. 402-405, specifically p. 402: cf. our App. A, p. 41; English transl.: K.S..

^[dd]For a rare glimpse into the communication between Kemmer and Weisskopf concerning this work see the letter of June 8, 1936 from Kemmer to Weisskopf (letter [430b] reprinted in [245], pp. 792-794). For the interest of Pauli in this problem see his letters of May 19, 1936 and of June 3, 1936 to Weisskopf (letters [427f] and [430a] reprinted in [245], pp. 788-790 (specifically p. 788) and pp. 790-792 (specifically p. 791), respectively.)

^[ee][102], p. 567 in the Russian original (cf. our App. A, p. 41), p. 7 of the reprint, p. 478 in the German transl.. English transl.: K.S..

and 2. eds., Chap. IV, § 19, pp. 193/194). Furthermore, he correctly notes that the probability for the vacuum decay of a photon into two photons vanishes – a modern consideration would refer to Furry’s theorem [247] to infer this – leaving as minimal possible case a decay into three photons. Relying on the formalism used by Heisenberg in [36], M. P. Bronshtein (Leningrad Physico-Technical Institute, USSR) in 1937 concludes [104] (preceded by a corresponding short note in 1936 [70]) that in free Minkowski space (spontaneous) photon splitting is not possible at all within the framework of quantum electrodynamics^[ff]. On the other hand, photon splitting in the presence of an external field is possible and Williams discussed in 1935 [63], § 10, pp. 47-49, for the first time the splitting of a photon in the presence of an electric particle (electric field).

Within the framework of quantum electrodynamics, the further investigation of such processes as photon-photon scattering, Delbrück scattering, and photon splitting continued in the 1950’s only and falls, therefore, beyond the time frame of the present exposition. In the 1930’s and 1940’s these subjects have been considered both within Born-Infeld electrodynamics and in quantum electrodynamics. Interestingly, however, the theoretical study of the propagation of light in constant homogeneous magnetic and electric fields has been performed in the period under review within Born-Infeld electrodynamics only. Corresponding studies within QED began in the 1950’s only (J. S. Toll).

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^[ff]For a modern argument see [248], sec. III, p. 2343. Note that in eq. (31) the first sum sign should be read as a product sign.

Appendices

Appendix A

Original language versions of the quotations in the main text:

- P. 3: Kepler ([161], p. 23, reprint (1859) p. 142, reprint (1939) p. 32, proposition 26): “*Lucis radii se mutuò neque colorant, neque illustrant, neque impediunt ullo modo. . . . Sanè vt nec physicus motus alter alterum mouet.*”
- P. 3: Ibn al-Haytham ([166], book I, chap. 5, item 29, p. 17, reprint [171], book I, chap. 7, p. 57, item [6.87]): “*Luces ergo non admiscétur in aere, sed quælibet illarú extenditur super uerticationes rectas; & illę uerticatiões sunt æquidistátés, & secátés se, & diuersi situs. Et forma cuiuslibet lucis extéditur super oés uerticatiões, quę possunt extendi in illo aere ab illa hora: neq; tamé admiscentur in aere, nec aer tingitur per eas, sed pertranseunt per ipsius diaphanitaté tantum, & aer non amittit suá formá.*”
- P. 4: Huygens ([173], p. 20): “*Une autre, & des plus merueilleuses prepietez de la lumiere est que, quand il en vient de diuers costez, ou mesme d’opposez, elles font leur effet l’une à travers l’autre sans aucun empéchement.*”
- P. 4: Vavilov ([11], p. 555, reprint [175], p. 234): “Упрек, который в XVIII. в. часто делали ньютонической теории, заключался именно в том, что должны обнаруживаться соударения световых корпускул, т. е. нарушение суперпозиции. Выходом из затруднения было допущение крайней малости корпускул: «Знаю, – писал Ломоносов³[K.S.: orig. footn.] по адресу защитников корпускулярной гипотезы, – что вы разделяете материю света на толь малые частицы и толь редко одну по всемирному пространству поставяете, что все оное количество может сжаться и уместиться в порожних скважинах одной песчинки».”
- P. 8: Vavilov ([11], § 2, pp. 556/557, reprint [175], p. 236): “Едва ли не самые большие мгновенные плотности радиации в лабораторных условиях получаются при помощи света конденсированной искры. Концентрируя этот свет линзой, легко добиться мгновенных значений плотности лучистой энергии, превышающих соответствующие значения у поверхности Солнца. Средняя плотность в этом случае мала вследствие краткой длительности и редкости искр, но гипотетический эффект «соударений» световых квантов должен быть пропорциональным квадрату мгновенной плотности, поэтому искра оказывается значительно выгоднее, чем, например,

³[K.S.: orig. footn.] М. В. Ломоносов, Слово о происхождении света. Собрание разных сочинений, ч. III, 1803, стр. 155. (K.S.: M. V. Lomonosov, Slovo o proiskhozhdenii sveta. Sobranie raznykh sochinenii, ch. (pt.) III, 1803, str. (p.) 155 [179])

дуга. Наблюдения при этом производились с обычными предосторожностями, на фоне далеко отстоящих стенок сосуда, отклеенных черным бархатом; для контроля опыты повторялись со светом лампы накаливания, которая давала такую же среднюю плотность радиации; в обоих случаях результат был одинаково отрицательным.”

- P. 12: Kapitsa ([190], p. 31, [190], p. 40, reprints: 1. [191], p. 40. 2. [192], 3. ed. p. 375, 4. ed. p. 374): “В 30-х годах в Кавендишской лаборатории я осуществил метод получения магнитных полей по силе на порядок выше, чем до сих пор это было достигнуто. В одной беседе Эйнштейн пытался меня убедить экспериментально изучать влияние магнитного поля на скорость распространения света. Эти опыты уже делались, никакого эффекта не было обнаружено. В моих магнитных полях можно было бы поднять предел точности измерения порядка на два, поскольку эффект должен был зависеть от квадрата интенсивности магнитного поля. Я возражал Эйнштейну, что, согласно существующей картине электромагнитных явлений, не видно, откуда можно было бы ждать таково измеримого явления. Не находя возможности обосновать необходимость таких опытов, Эйнштейн, наконец, сказал: «Я думаю, что дорогой господь бог (*der liebe Gott*) не мог так создать мир, чтобы магнитное поле не влияло на скорость света». Конечно, это аргумент, с которым трудно спорить.”
- P. 15: Delbrück [25]: “... daß es sich um einen *Photoeffekt* an einem der unendlich vielen Elektronen in Zuständen negativer Energie handelt, die nach Diracs Theorie den ganzen Raum mit unendlicher Dichte erfüllen und die zu einem solchen Absorptionsprozeß vermöge ihrer Wechselwirkung mit dem Kern wohl befähigt wären.”
- P. 15: Delbrück [25]: “Eine solche Auffassung zwingt dann auch zu der Folgerung, daß diese Elektronen negativer Energie γ -Strahlen zu *streuen* vermögen, und zwar *kohärent*, analog dem Phänomen der *unverschobenen* Comptonlinie.”
- P. 17: Heisenberg ([214], letter [374] of June 16, 1934, pp. 331-333, specifically p. 332): “Delbrück war neulich hier und erzählte von seinen vergeblichen Versuchen, die kohärente Streuung zu rechnen. Er wäre sicher froh, wenn er die Arbeit gemeinsam mit einem anderen z.B. Weisskopf machen könnte (Sauter ist jetzt in Göttingen).”
- P. 19: Ebert ([3], pp. 381-383):
 “Zum Schluss erlaube ich mir noch, das obige Resultat auf einige astrophysikalische Fragen anzuwenden.
 Ist die Fortpflanzungsgeschwindigkeit des Lichtes von seiner Intensität in irgend einem merklichen Grade abhängig, so würde zu dem Umstande, dass die uns am Himmel in demselben Augenblicke entgegnetretenden Erscheinungen in Wirklichkeit sehr verschiedenen Zeiten angehören, noch die weitere

Complication hinzutreten, dass diese Zeiten selbst bei gleicher räumlicher Entfernung für die verschiedenen Objecte sehr verschieden wären. Bei den grossen Intensitätsunterschieden, die sich hier vorfinden, und den grossen Entfernungen, welche die Lichtstrahlen zu durchlaufen haben, ehe sie zu uns gelangen, konnten sich selbst kleine Unterschiede in der Fortpflanzungsgeschwindigkeit in hohem Grade geltend machen. Dies müsste z. B. bei den physischen Doppelsternen eintreten; hier haben wir zwei Lichtquellen, die zwar sehr angenähert gleich weit von uns abstehen, deren Lichtintensität sich aber im allgemeinen sehr erheblich voneinander unterscheidet. Trotzdem finden wir, dass, wenn es uns gelungen ist die Bahnen von Doppelsternen zu berechnen, die beiden Componenten wirklich zu gleicher Zeit an entsprechenden Punkten ihrer Bahnen erscheinen und mit ihrem gemeinsamen Schwerpunkte immer auf einer geraden Linien liegen. Diese Thatsache können wir also geradezu als neue Stütze für das von uns experimentell festgestellte Resultat heranziehen. Ein Beispiel möge übrigens noch zeigen, dass die von mir nachgewiesene Grenze für die Unabhängigkeit der beiden in Rede stehenden Grössen für die astronomische Praxis jedenfalls völlig ausreicht.

Der von Bessel berechnete, von Clark entdeckte Begleiter des Sirius besitzt nach den Berechnungen von Auwers und Peters eine ausserordentlich grosse Masse ($\frac{1}{2}$ bis $\frac{2}{3}$ der Siriusmasse selbst). Gleichwohl erscheint er uns nur als Stern etwa 9. Grösse, seine Helligkeit ist also gegen die seines Hauptsternes eine sehr geringe, nach Schönfeld ¹⁾[K.S.: orig. footn.] nur ca. $\frac{1}{1000}$ von der des Sirius. Oben wurde für Strahlen mittlerer Wellenlänge (für das Natriumlicht) gefunden, dass bei Abschwächung des Lichtes von der Intensität 1 bis zur Intensität $\frac{1}{33}$ die Fortpflanzungsgeschwindigkeit sich noch nicht um $\frac{1}{500\ 000}$ ändert. Gehen wir von diesem Grenzwerthe aus, d. h. nehmen wir an, dass sich bei Helligkeitsdifferenzen von 33:1 die Fortpflanzungsgeschwindigkeit gerade noch um diesen Betrag unterscheiden könne, und dass derselbe proportional mit dem Intensitätsunterschiede wachse, so würde das Licht des Begleiters in dem vorliegenden Beispiele in jeder Secunde um $30 \times 0,6$ oder 18 km hinter dem Lichte des Hauptsternes zurückbleiben. Die Entfernung des Siriusystems beträgt in Lichtzeit etwa 30 Jahre. Nehmen wir an, es seien genau 30 Jahre, so würde das Licht des Begleiters:

$$\frac{300\ 000}{299\ 982} \times 30 = 30,0018$$

Jahre gebrauchen, um zu uns zu gelangen, d. h. von zwei gleichzeitig ausgehenden Lichtstrahlen würde der des Begleiters immer nur etwa 0,7 Tag später eintreffen, als der vom Sirius selbst ausgesandte. Da aber die Umlaufzeit beider Körper um ihren gemeinsamen Schwerpunkt etwa 50 Jahre beträgt, so ist jene Zeitdifferenz und die ihr entsprechende Ortdifferenz zu vernachlässigen. Die gemachten Annahmen sind jedenfalls sehr ungünstige; wir können

¹⁾[K.S.: orig. footn.] Schönfeld, Die dunklen Fixsternbegleiter. Mannheimer Verein für Naturkunde. 30. Jahresbericht. (K.S.: cf. [218])

also sicher bei allen Bahnbestimmungen von der etwa noch vorhandenen Abhängigkeit der Fortpflanzungsgeschwindigkeit von der Intensität, deren Betrag unter den durch das Experiment festgestellten Grenzen liegt, absehen.

Das erhaltene Resultat ist ferner bei den Anwendungen des Doppler'schen Principes von Bedeutung, wo die relativen Geschwindigkeiten der Gestirne in der Richtung der Sehlinie aus Aenderungen in der mittleren Brechbarkeit isolirter Spectrallinien bestimmt werden. Hier liegen in den einzelnen Fällen oft sehr grosse Helligkeitsunterschiede vor, und es ist folglich für die Anwendbarkeit dieses Principes wichtig, direct nachgewiesen zu haben, dass diese Helligkeitsunterschiede nicht mit in Frage kommen."

P. 29: Einstein ([227], letter 69, pp. 169/1970): "Dein Versuch, die Quantenfrage des Feldes von einer neuen Seite anzugreifen, hat mich sehr interessiert, aber nicht gerade überzeugt. Ich glaube immer noch, daß die Wahrscheinlichkeits-Interpretation trotz ihres großen Erfolges keine gangbare Möglichkeit für die relativistische Verallgemeinerung bildet. Auch die Begründung der Wahl einer Hamiltonfunktion für das elektromagnetische Feld mit der Analogie zur speziellen Relativitätstheorie hat mich nicht überzeugt. Ich fürchte, daß wir alle die wirkliche Lösung dieses harten Problems nicht erleben werden."

P. 29: Born ([227], pp. 170/1971): "Zweierlei Einwände hatte Einstein gegen meine Ideen: Der erste beruhte auf seiner Ablehnung der Wahrscheinlichkeits-Interpretation der Quantenmechanik. Dabei geht es um eine Prinzipienfrage des Denkens, von der noch mehr die Rede sein wird. Er traf die von Infeld und mir entworfene Theorie eigentlich nicht, da wir selber mit der Einfügung derselben in die Quantenmechanik nicht fertig wurden; er verurteilte unsere Bemühungen in dieser Richtung als grundsätzlich falsch. Der zweite Einwand Einsteins bezog sich auf unsere ursprüngliche, ›klassische‹ Feldtheorie, die in sich geschlossen und widerspruchsfrei war. Sie beruhte auf folgender Analogie: In der speziellen Relativitätstheorie wird die kinetische Energie eines Teilchens, die in der klassischen Mechanik dem Quadrat der Geschwindigkeit proportional ist, durch einen etwas komplizierteren Ausdruck dargestellt; für Geschwindigkeiten, die klein gegen die des Lichtes sind, geht er in den klassischen Ausdruck über, weicht aber davon ab, wenn die Geschwindigkeit der des Lichtes nahe kommt. In der Maxwellschen Elektrodynamik ist die Energiedichte quadratisch in den Feldstärken; ich ersetzte sie durch einen allgemeinen Ausdruck, der in den klassischen übergeht, wenn die Feldstärken klein gegen eine ›absolute Feldstärke‹ sind, aber davon abweichen, wenn das nicht der Fall ist. Daher ergab sich ganz von selbst, daß die Gesamtenergie des Feldes einer Punktladung endlich ist, während sie im Maxwellschen Feld unendlich groß wird. Das absolute Feld muß als eine neue Naturkonstante angesehen werden.

Diese Analogie-Konstruktion fand Einstein nicht überzeugend. Infeld und mir schien sie lange anziehend. Wir gaben die Theorie aus ganz anderen Gründen

auf, nämlich weil es uns nicht gelang, sie mit den Prinzipien der Quantenfeldtheorie in Einklang zu bringen.

Jedenfalls war dieser Ansatz der erste Versuch, die Schwierigkeiten in der Mikro-Physik durch eine nicht-lineare Theorie zu beheben. Heisenbergs Theorie der Elementarteilchen, die heute viel von sich reden macht, ist auch nicht-linear. Aber das gehört nicht hierher.”

- P. 31: Heisenberg ([241], p. 126): “Das Thema der vorliegenden Arbeit geht auf eine Frage zurück, die mir Kollege Debye stellte.”
- P. 32: Heisenberg ([214], p. 331, letter of June 17, 1934 to N. Bohr): “Debye hatte die Idee, daß die Sonnenkorona durch diese Streuung von Licht entsteht; zu dieser These würde der obige Wert $[(e^2/\hbar c)^4(\hbar/mc)^2]$ für den Wirkungsquerschnitt ausgezeichnet passen. Aber, wie gesagt, man muß noch abwarten, ob alle Rechnungen in Ordnung sind.”
- P. 32: Heisenberg ([214], letter [374] of June 16, 1934, pp. 331-333, specifically p. 332): “Dieser Wert scheint gut zu der Idee von Debye zu passen, daß die Sonnenkorona durch diese Streuung von Licht an Licht entsteht.”
- P. 34: Pauli ([245], letter [423b] of December 5, 1935, pp. 777/778, specifically p. 778): “Das „Euler-Kockel“-Problem für kurze Wellen sieht mir im Moment etwas trübe aus.”
- P. 34: Pauli ([245], letter [425c] of January 20, 1936, pp. 780-782, specifically p. 782): “Das Problem der Streuung von Licht an Licht bei kurzen Wellen habe ich nun, nach Besprechung mit Oppenheimer, definitiv als zu kompliziert aufgegeben.”
- P. 35: Pauli ([214], letter [412] of June 15, 1935, pp. 402-405, specifically p. 402): “Weisskopf ist am Delbrückschen Problem und die dabei auftretenden Fragen der Subtraktionsphysik werden sehr unschön.”
- P. 35: Akhiezer ([102], p. 567): “Эффективный поперечник рассеяния имеет максимум при $\hbar\omega \sim mc^2$.”

Appendix B

Extract from the book *Ondes et Mouvements* (1926) by L. de Broglie ([9], Chap. XI, Sec. 2, pp. 96-98. English transl.: K.S.. The English translation is appended after the original French text.):

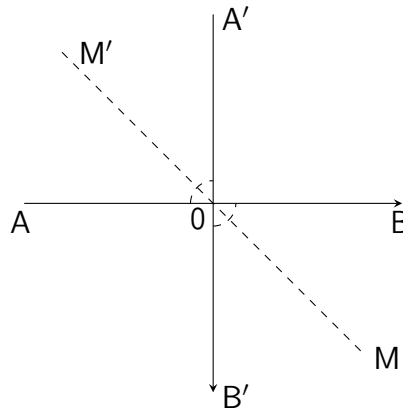
“**2. Chocs entre atomes de radiation.** – Examinons une autre question assez curieuse : deux quanta de lumière peuvent-ils échanger de l’énergie par choc, autrement dit peuvent-ils changer de fréquence à la suite d’une collision ? L’expérience n’a rien révélé de semblable et un tel phénomène est tout à fait étranger aux théories classiques. Cependant, il existe peut-être une raison de le croire possible au moins en principe. Dans la dernière partie de ce livre, je montrerai qu’à la suite des travaux de MM. Bose et Einstein et des miens, il est légitime de considérer le rayonnement noir comme un gaz d’atomes de lumière ; des raisonnements statistiques appliqués à nos conceptions ondulatoires nous conduiront à la loi Planck, mais elles ne nous montreront pas par quel mécanisme cette répartition des quanta entre les diverses valeurs de l’énergie se trouve réalisée et maintenue. Il paraît assez tentant de supposer que l’équilibre résulte des échanges d’énergie et de quantité de mouvement entre quanta dues à leur interaction mutuelle, à leurs chocs au sens le plus général du mot.

Peut-être est-il donc intéressant d’étudier un peu ce genre de chocs.

Il serait facile de résoudre le problème général de la rencontre de deux quanta de fréquences différentes comme nous l’avons fait pour l’effet Compton.

Pour ne pas multiplier les formules, je me contenterai d’envisager un cas très simple. Supposons qu’à l’aide de collimateurs, on fasse se croiser à angle droit deux faisceaux monochromatiques de même fréquence, aucune condition de cohérence n’étant d’ailleurs exigée. Représentons schématiquement ces deux faisceaux par des lignes droites AB et $A'B'$ (*fig. 9*) se croisant en O .

Fig. 9.



Observons, s’il en existe, la lumière diffusée au point O dans la direction OM bissectrice de l’angle $\widehat{BOB'}$. Si, par suite d’un choc, un quantum est diffusé suivant

OM, l'autre quantum sera diffusé suivant OM'. Soient ν la fréquence initiale, ν_1 et ν_2 les fréquences des quanta diffusés vers M et vers M'. Les équations de conservation s'écrivent

$$\begin{aligned} h\nu_1 + h\nu_2 &= 2 h\nu, \\ \frac{h\nu_1}{c} - \frac{h\nu_2}{c} &= 2 \frac{h\nu}{c} \cos 45^\circ ; \end{aligned}$$

d'où

$$\begin{aligned} \nu_1 &= \nu(1 + \cos 45^\circ) = 1,7 \nu, \\ \nu_2 &= 0,3 \nu. \end{aligned}$$

Si la longueur d'onde des faisceaux employés était $\lambda = 0,68$, la radiation observée en M correspondrait à $\lambda_1 = \frac{0,68}{1,7} = 0,4$. En visant le point de croisement de deux faisceaux rouges, on recueillerait de la lumière violette. Ce serait un beau phénomène! Je ne sais s'il existe et, en ce cas, s'il serait observable, mais, si un jour il était décelé, sa place serait toute marquée dans l'ensemble de nos nouvelles vues théorétiques sur les radiations."

English translation:

"2. Collisions between atoms of radiation. – We are considering another interesting problem: Can two light quanta exchange energy in a collision, or speaking differently, can they change the frequency in course of a collision? Experience does not reveal anything similar and such a phenomenon is rather alien to classical theories. However, there may be a reason for considering this to be possible, at least in principle. In the last part of this book, I will show, as a result of work done by Messrs. Bose and Einstein and myself, that it is legitimate to consider the black radiation in a gas of atoms of light; statistical reasoning applied to our wave conceptions leads us to the Planck law, but it does not explain by what mechanism this redistribution of quanta among the different energy levels is achieved and maintained. It seems quite tempting to assume that the equilibrium results from exchanges of energy and momentum among quanta as a result of their mutual interactions, their collisions in the most general sense of the word.

Consequently, it is perhaps interesting to somewhat investigate this kind of collisions.

It is easy to solve the problem of the encounter of two quanta with different frequencies the same way as we did for the case of the Compton effect. In order to not multiply formulae, I will only consider a very simple case.

Consider, using collimators, intersecting at a right angle two monochromatic beams of the same frequency, incidentally, no coherence condition is being required. We represent the two beams schematically by means of the two perpendicular lines AB and A'B' (*fig. 9*) intersecting each other in O.

Fig. 9. (K.S.: see above)

We observe whether any light scatters from the point O into the direction OM bisecting the angle $\widehat{BOB'}$. If, through a collision, a quantum is scattered along OM, the other quantum is scattered along OM'. Let ν be the initial frequency, and ν_1 and ν_2 the frequencies of the quanta scattered towards M and towards M'. The equations of conservation are

$$\begin{aligned} h\nu_1 + h\nu_2 &= 2 h\nu, \\ \frac{h\nu_1}{c} - \frac{h\nu_2}{c} &= 2 \frac{h\nu}{c} \cos 45^\circ ; \end{aligned}$$

wherefrom

$$\begin{aligned} \nu_1 &= \nu(1 + \cos 45^\circ) = 1,7 \nu, \\ \nu_2 &= 0,3 \nu. \end{aligned}$$

If the wavelength of the beams used is $\lambda = o^\mu, 68$, the radiation observed in M would correspond to $\lambda_1 = \frac{0,68}{1,7} = o^\mu, 4$. Aiming at the crossing point with two red beams, one would obtain violet light. This would be a beautiful phenomenon! I do not know if it exists, and in that case, whether it is observable, but if one day it was detected it would assume a distinguished place within the framework of our new theoretical ideas on radiation.”

Appendix C

On the experimental result of Banwell and Farr, Proc. Roy. Soc. London
A 175(1940)1 [135]:

Given the present-day interest in the type of experiment Banwell and Farr reported in 1940 [135] it seems to be interesting to contemplate the question what influence might have led to the non-null result (which Banwell and Farr themselves – see quote in subsec. 2.2.2 in the main text – considered as likely to be erroneous). In the following we will attempt to hypothesize about a possible reason for their non-null result for the refractive index of the vacuum in a magnetic field which is much larger than the present-day expectation based on the Euler-Kockel-Heisenberg effective Lagrangian of QED (and of opposite sign). Reading the carefully written article by Banwell and Farr one notices that they say very little about one important optical element used in their experimental set-up, namely, the mirrors employed in the Michelson interferometer. They are only characterized as optical flats, silvered or half-silvered (p. 1, begin of the second paragraph; pp. 3/4). The point is that two of the mirrors used by Banwell and Farr in the experiment are subject – at least – to magnetic stray fields: one mirror (mirror O , cf. fig. 1 on p. 3 of [135] redisplayed in our Fig. 2) at the end of the arm of the Michelson interferometer placed in the strong magnetic field, and a semi-transparent mirror (mirror N , cf. Fig. 2) used to split the initial light beam into the two arms of the Michelson interferometer. Both mirrors are just located a few decimeters away from the coils generating the strong magnetic field. This aspect of the experimental set-up is neither mentioned nor discussed by Banwell and Farr. Let us shortly consider the physical situation at the mirror (mirror O) at the end of the arm of the Michelson interferometer placed in the strong magnetic field (The semi-permeable mirror N is also subjected to stray fields but the light in both arms of the Michelson interferometer interacts with N in a fairly symmetric manner and the mirror N can, therefore, be left outside the current consideration.). The light from this arm falls perpendicularly onto the mirror and is perpendicularly being reflected at the silver layer (by the way, whose thickness is not given in the article by Banwell and Farr). In this metallic reflection (by a metallic medium with the complex refractive index $n = n' + i n'' = n'(1 + i\kappa)$) the reflected light beam experiences a phase shift φ relative to the incident light beam given by the equation^[gsg]:

$$\tan \varphi = \frac{2 n' \kappa}{n'^2 + n'^2 \kappa^2 - 1} . \quad (\text{C.1})$$

For massive silver at room temperature and light of $\lambda = 546.1$ nm (equivalent to a photon energy of 2.27 eV) one has $n' = 0.17$, $n'\kappa = 3.31$ ([251], Table IX, p. 356, interpolated by means of [252]) resulting in a phase shift φ of about 0.59 rad (corresponding to 34°). Now, once the refractive index of the mirror material (in this

^[gsg][249], p. 86, eq. (40); for a modern discussion see, e.g., [250], sec. 2.4, p. 35, eq. (2.4.14); N.B. For simplicity we neglect in the present discussion the influence of any intermediate glass layer.

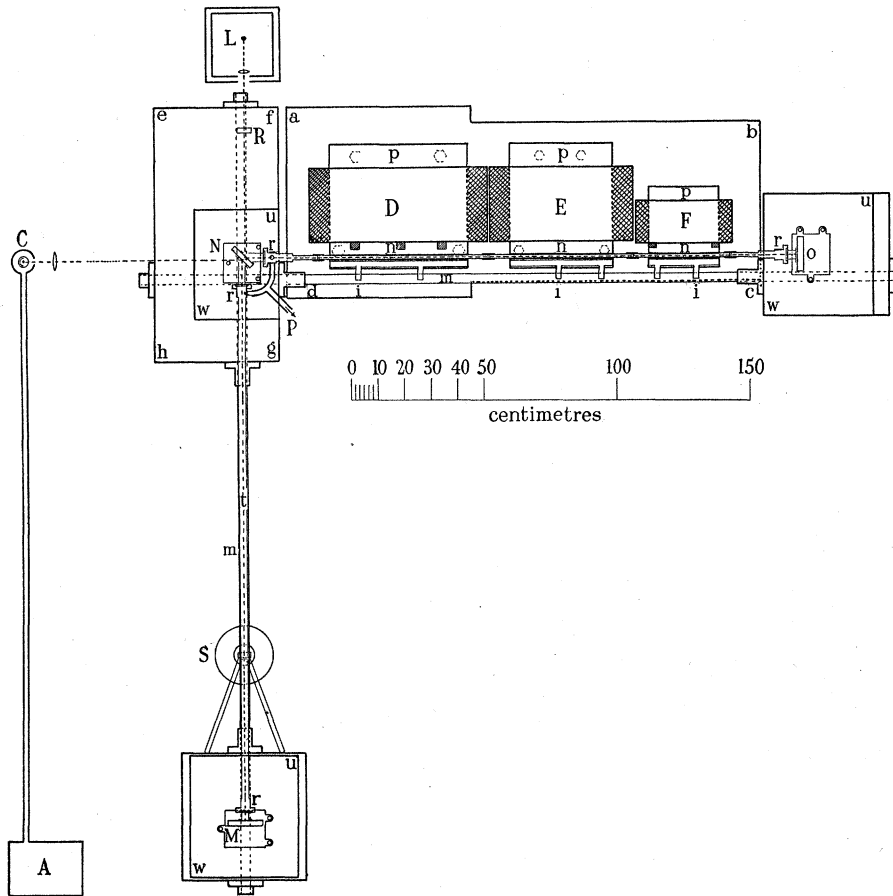


Figure 2: Top view of the Michelson interferometer used by Banwell and Farr (re-display of Fig. 1 of [135], p. 3). L is the light source while observation is made at C (photoelectric cell). D , E , F are the electromagnets of the arm subjected to the magnetic field, M , O are mirrors (silvered flats) while N is a half-silvered flat.

case, silver) changes the phase shift φ also experiences a corresponding change $\Delta\varphi$ to some $\bar{\varphi} = \varphi + \Delta\varphi$. Once this change in the mirror properties (and, consequently, the change in the phase shift at the mirror) occurs only for one of the mirrors at the end of the two arms of the Michelson interferometer the interferometric pattern observed in the experiment will also change. If this phenomenon is not properly taken care of the corresponding change in the interferometric pattern can lead to a misinterpretation of results. As we will detail further below it seems to be conceivable that the change in the mirror properties (mirror O) effected by the stray magnetic field may have led to the non-null result reported by Banwell and Farr.

In their Michelson interferometer experiment, Banwell and Farr have interpreted the observed change in the interference pattern once the magnetic field acting on one interferometer arm had been switched on as resulting from a changed vacuum

velocity of light $\bar{c} = f\bar{\lambda}$ (f is the frequency of the monochromatic light wave). Hypothesize now that the observed change in the interference pattern in fact completely originated from a change in the refractive index of the silver layer of the mirror O placed in the (stray) magnetic field. Then, according to the interpretation applied by Banwell and Farr the optical path of length l ($= 2 \times 1.17 \text{ m} = 2.34 \text{ m}$) placed in the magnetic field would be stretched out by n wave cycles of wavelength $\bar{\lambda}$ (We also have taken into account the phase shift/delay under reflection.)

$$l = n \bar{\lambda} - \frac{\varphi}{2\pi} \bar{\lambda}. \quad (\text{C.2})$$

while in reality it should be written as

$$l = n \lambda - \frac{\bar{\varphi}}{2\pi} \lambda. \quad (\text{C.3})$$

From the equations (C.2), (C.3) follows that the assumed change in the vacuum velocity of light $\Delta c = \bar{c} - c$ can be expressed as a change in the phase shift under reflection according to the equation

$$\Delta\varphi = -2\pi \frac{l}{\lambda} \frac{\Delta c}{\bar{c}} \quad (\text{C.4})$$

$$\simeq -2\pi \frac{l}{\lambda} \frac{\Delta c}{c} \quad (\text{C.5})$$

where equation (C.5) represents the relation at leading order of the small quantity $\Delta c/c$. Inserting now the values given by Banwell and Farr into eq. (C.5) one finds the following. The change in the interference pattern observed in the Michelson interferometer which has been interpreted by Banwell and Farr as a change in the (vacuum) velocity of light in a magnetic field could have arisen equally well from a different source in the experimental apparatus. Let us assume that in the presence of the applied strong magnetic field stray fields might have modified the reflective properties of the silver mirror (mirror O) at the end of the arm of the Michelson interferometer placed in the magnetic field. Then, a corresponding change in the phase shift under reflection experienced by the light beam propagating in this arm of the Michelson interferometer of the size

$$\Delta\varphi \simeq -2\pi (4.7 \pm 2.6) \cdot 10^{-3}. \quad (\text{C.6})$$

might have modified the interference pattern equivalently. From eq. (C.1) it is clear that any change in the (complex) refractive index of the silver layer of the order of $\Delta\kappa/\kappa$, $\Delta n'/n' \sim 10^{-2}$ will result in the right order of magnitude of change in the phase shift under reflection given by eq. (C.6).

Let us ponder now the question if it is conceivable that a magnetorefractive effect might result in a change in the refractive index of the silver mirror that has the right magnitude (We primarily imagine that the magnetic stray field is parallel to

the mirror surface.). Unfortunately, there is apparently little information available in the literature in this respect. Gostishchev and Sobol' [253] estimate for low temperatures, however, and a magnetic field of the order of 10^5 oersted (corresponding to a magnetic induction of 10 T in vacuo) that for visible light the change in the reflection coefficient (compared to the situation with no magnetic field applied) for a metal with a closed Fermi surface is not larger than 10^{-3} (the same applies to the refractive index). On one hand side, the estimate of Gostishchev and Sobol' is somewhat smaller than required by eq. (C.6) and on the other hand, they consider the case of low temperatures while the experiment of Banwell and Farr has been performed at room temperature. To broaden the perspective, let us mention that the Drude model of metals (free gas of conduction electrons) relates the conductivity in a metal to its refractive index. Consequently, any study of the phenomenon of magnetoresistance in a metal has in principle its bearing on its magnetorefractive properties. Of course, this connection can only be of heuristic value as the reliability of the Drude model is restricted to the domain of infrared light, while the experiment of Banwell and Farr has been performed using visible light. Magnetoresistance effects are primarily related to two phenomena: the deviation of the Fermi surface from a spherical shape (cf., e.g., [254], Sec. 12.3, p. 490-495, specifically p. 494) and the influence of size effects as they occur in thin films. For experimental results see, e.g., [255, 256].

To conclude, in principle magnetorefractive effects in silver mirrors exist which might lead to a change in the phase shift under reflection in accordance with eq. (C.6). The present state of research reflected in the literature, however, is insufficient to decide the question whether these magnetorefractive effects might have the right order of magnitude to explain the non-null result by Banwell and Farr.

Appendix D

Some formulas for the electromagnetic field strength tensor:

$$F^{\mu\nu} = \begin{pmatrix} 0 & -\frac{1}{c}E_1 & -\frac{1}{c}E_2 & -\frac{1}{c}E_3 \\ \frac{1}{c}E_1 & 0 & -B_3 & B_2 \\ \frac{1}{c}E_2 & B_3 & 0 & -B_1 \\ \frac{1}{c}E_3 & -B_2 & B_1 & 0 \end{pmatrix} \quad (\text{D.1})$$

The (symmetric) stress-energy-momentum tensor of the free electromagnetic field reads:

$$T^{\mu\nu} = \frac{1}{\mu_0} \left[F^{\mu\alpha} F^\nu{}_\alpha - \frac{1}{4} g^{\mu\nu} F^{\alpha\beta} F_{\alpha\beta} \right] \quad (\text{D.2})$$

After some calculation one finds:

$$T^{\mu\nu} T_{\mu\nu} = 2 \epsilon_0^2 \left[(\mathbf{E}^2 - c^2 \mathbf{B}^2)^2 + 2 c^2 (\mathbf{E}\mathbf{B})^2 \right] \quad (\text{D.3})$$

$$= 8 \mathcal{L}_0^2 + \frac{4}{\mu_0^2} (\mathbf{E}\mathbf{B})^2 \quad (\text{D.4})$$

$$= 4 \left[(T_{00})^2 - \frac{1}{c^2} \mathbf{S}^2 \right] = -4 T^{0\nu} T_{0\nu} \quad (\text{D.5})$$

with the free field Lagrange density

$$\mathcal{L}_0 = -\frac{1}{4\mu_0} F^{\mu\nu} F_{\mu\nu} = \frac{1}{2} \epsilon_0 (\mathbf{E}^2 - c^2 \mathbf{B}^2) = \frac{1}{2} \left(\epsilon_0 \mathbf{E}^2 - \frac{1}{\mu_0} \mathbf{B}^2 \right) \quad (\text{D.6})$$

and

$$T_{00} = \frac{1}{2} \epsilon_0 (\mathbf{E}^2 + c^2 \mathbf{B}^2) = \frac{1}{2} \left(\epsilon_0 \mathbf{E}^2 + \frac{1}{\mu_0} \mathbf{B}^2 \right). \quad (\text{D.7})$$

One recognizes from the eqs. (D.4), (D.5), that the square of the Poynting vector $\mathbf{S} = \frac{1}{\mu_0} \mathbf{E} \times \mathbf{B}$ is related to the field invariant $(\mathbf{E}\mathbf{B})^2$ (By virtue of the Lagrange identity for three-dimensional vectors $\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}$: $(\mathbf{a} \times \mathbf{b}) \cdot (\mathbf{c} \times \mathbf{d}) = (\mathbf{a} \cdot \mathbf{c})(\mathbf{b} \cdot \mathbf{d}) - (\mathbf{b} \cdot \mathbf{c})(\mathbf{a} \cdot \mathbf{d})$).

Appendix E

Reminiscences of W. Heisenberg onto his conversations with H. Euler concerning the scattering of light by light in advance of the thesis research of the latter [257], chap. 13, pp. 220-222, 225 (pp. 220-222, 225 of the reprint, pp. 160-162, 164 of the English translation. The English translation is appended after the original German text.):

“So kam ich oft mit Euler zusammen, und wir berieten daher über die möglichen Konsequenzen der Diracschen Entdeckung und der Umwandlung von Energie in Materie.

»Wir haben doch von Dirac gelernt«, so könnte Euler etwa gefragt haben, »daß ein Lichtquant, das an einem Atomkern vorbeifliegt, sich dabei in ein Paar von Teilchen, ein Elektron und ein Positron, verwandeln kann. Bedeutet das eigentlich, daß ein Lichtquant aus einem Elektron und einem Positron besteht? Dann wäre das Lichtquant so eine Art Doppelsternsystem, in dem Elektron und Positron umeinander kreisen. Oder ist das eine falsche anschauliche Vorstellung?«

»Ich glaube nicht, daß ein solches Bild viel Wahrheit enthält. Denn aus diesem Bild würde man doch schließen, daß die Masse eines solchen Doppelsterns nicht viel kleiner sein sollte als die Summe der Massen der beiden Teile, aus denen es besteht. Und man könnte auch nicht einsehen, warum dieses System sich immer mit Lichtgeschwindigkeit durch den Raum bewegen muß. Es könnte doch auch irgendwo zur Ruhe kommen.«

»Was soll man aber dann über das Lichtquant in diesem Zusammenhang sagen?«

»Man darf vielleicht sagen, daß das Lichtquant virtuell aus Elektron und Positron besteht. Das Wort ›virtuell‹ deutet an, daß es sich um eine Möglichkeit handelt. Der eben ausgesprochene Satz behauptet dann nur, daß das Lichtquant sich eben in gewissen Experimenten möglicherweise in Elektron und Positron zerlegen läßt. Mehr nicht.«

»Nun könnte in einem sehr energiereichen Stoß ein Lichtquant doch vielleicht auch in zwei Elektronen und zwei Positronen verwandelt werden. Würden Sie dann sagen, daß das Lichtquant virtuell auch aus diesen vier Teilchen besteht?«

»Ja, ich glaube, das wäre konsequent. Das Wort ›virtuell‹, das die Möglichkeit bezeichnet, erlaubt ja die Behauptung, daß das Lichtquant virtuell aus zwei oder vier Teilchen besteht. Zwei verschiedene Möglichkeiten schließen sich ja nicht aus.«

»Aber was gewinnt man dann noch mit einem solchen Satz?« wandte Euler ein. »Dann kann man doch gleich sagen, daß jedes Elementarteilchen virtuell aus irgendeiner beliebigen Zahl von anderen Elementarteilchen besteht. Denn bei sehr energiereichen Stoßprozessen wird schon irgendeine beliebige Zahl von Teilchen entstehen können. Das ist doch fast keine Aussage mehr.«

»Nein, so beliebig sind Zahl und Art der Teilchen denn doch nicht. Nur solche Konfigurationen von Teilchen werden als mögliche Beschreibung des einen darzustellenden Teilchens in Betracht kommen, die die gleiche Symmetrie haben wie das ursprüngliche Teilchen. Statt Symmetrie könnte man noch genauer sagen: Trans-

formationseigenschaft gegenüber solchen Operationen, unter denen die Naturgesetze unverändert bleiben. Wir haben doch schon aus der Quantenmechanik gelernt, daß die stationären Zustände eines Atoms durch ihre Symmetrieeigenschaften charakterisiert sind. So wird es eben auch bei den Elementarteilchen sein, die ja auch stationäre Zustände aus Materie sind.«

Euler war noch nicht so recht zufrieden. »Das wird doch reichlich abstrakt, was Sie jetzt sagen. Es käme wohl mehr darauf an, sich Experimente auszudenken, die anders ablaufen, als man bisher angenommen hätte, und zwar deshalb anders, weil die Lichtquanten virtuell aus Teilchenpaaren bestehen. Man würde doch vermuten, daß man wenigstens qualitativ vernünftige Resultate bekommt, wenn man das Bild vom Doppelsternsystem einen Moment ernst nimmt und fragt, was nach der früheren Physik daraus folgen sollte. Zum Beispiel könnte man sich für das Problem interessieren, ob zwei Lichtstrahlen, die sich im leeren Raum kreuzen, wirklich so ungehindert durcheinander hindurchgehen, wie man bisher immer angenommen hat und wie die alten Maxwellschen Gleichungen es fordern. Wenn in dem einen Lichtstrahl virtuell, das heißt als Möglichkeit, Paare von Elektronen und Positronen vorhanden sind, so könnte der andere Lichtstrahl doch an diesen Teilchen gestreut werden; also müßte es eine Streuung von Licht an Licht geben, eine gegenseitige Störung der beiden Lichtstrahlen, die man aus der Diracschen Theorie ausrechnen könnte und die auch experimentell zu beobachten wäre.«

»Ob man so etwas beobachten kann, hängt natürlich davon ab, wie groß diese gegenseitige Störung ist. Aber Sie sollten ihre Wirkung unbedingt ausrechnen. Vielleicht finden die Experimentalphysiker dann auch Mittel und Wege, sie nachzuweisen.«

»Eigentlich finde ich diese Philosophie des ›als ob‹, die hier betrieben wird, doch sehr merkwürdig. Das Lichtquant verhält sich in vielen Experimenten so, ›als ob‹ es aus einem Elektron und einem Positron bestünde. Es verhält sich auch manchmal so, ›als ob‹ es aus zwei oder noch mehr solchen Paaren bestünde. Scheinbar gerät man in eine ganz unbestimmte verwaschene Physik hinein. Aber man kann aus der Diracschen Theorie doch die Wahrscheinlichkeit dafür, daß ein bestimmtes Ereignis eintritt, mit großer Genauigkeit berechnen, und die Experimente werden das Ergebnis schon bestätigen.«

...

Euler berechnete zusammen mit einem anderen Mitglied meines Seminars, Kockel, die Streuung von Licht an Licht, und obwohl der experimentelle Nachweis hier nicht so direkt geführt werden konnte, besteht heute wohl kein Zweifel mehr daran, daß es die von Euler und Kockel behauptete Streuung wirklich gibt.”

English translation:

“And so we would talk about atomic physics instead and, in particular, about the possible consequences of Dirac’s discovery, and the transformation of energy into matter.

“Dirac has shown,” Euler said, “that when a light quantum flies past an atomic nucleus, it may change into a pair of particles –an electron and a positron. Does this

mean the light quantum itself consists of an electron and a positron? In that case, it would be a kind of double star, one in which the electron and positron revolve about each other. Or is this a false picture?"

"I don't think it's very convincing. You see, the mass of a double star cannot be much smaller than the sum of the masses of its constituent parts. Nor would it necessarily have to move through space with the velocity of light. There is no reason why it should never come to rest."

"But, what *can* we say about the light quantum in this context?"

"Perhaps that is virtually made up of an electron and a positron. The word 'virtually' means that we are dealing with a possibility. In that case, my assertion means no more than that the light quantum may, in certain experiments, split up into an electron and a positron—noting more."

"Well, in a very high-energy impact, a light quantum might easily be transformed into two electrons and two positrons. Does that mean that it is virtually made up of these four particles as well?"

"Yes, I believe that would be the consistent view. Since the term 'virtually' denotes possibilities, we are entitled to say that the light quantum is virtually made up of two of four particles. Two different possibilities do not necessarily exclude each other."

"But what is the advantage of this sort of assertion?" Euler asked. "We might equally well say that every elementary particle is virtually made up of any number of other particles. After all, any number of particles might be created during high-energy collisions. In that case our statement says very little indeed."

"I should not put it like that, for, you see, the number and type of particles are not as arbitrary as all that. Only such configurations may be considered possible descriptions of a particular particle as have the same symmetry as the original particle. Instead of 'symmetry,' we might say more precisely: transformation characteristics under operations that leave the physical laws unchanged. After all, quantum mechanics has taught us that the stationary states of an atom are characterized by their symmetries. Things are probably much the same with elementary particles, which, when all is said and done, are simply stationary states of matter."

Euler was still not fully satisfied. "The whole argument is a bit too abstract for my liking. What we probably ought to be doing is to think up experiments that would lead to unexpected results, and this precisely because light quanta are virtually made up of pairs of particles. It seems reasonable to assume that we should obtain at least qualitatively satisfactory results if we stuck to the model of the double star, and asked what conclusions orthodox physics would draw. For instance, we could investigate whether or not two light rays crossing in empty space really pass through each other with no interaction, as we have assumed until now, and as the old Maxwellian equations demand. If pairs of electrons and positrons are virtually present, i.e., contained as a possibility, in a light ray, then another light ray ought to be scattered by these particles; hence there would be deflection of light by light, that is, an interaction of the two light rays. We ought to be able to demonstrate its existence and to calculate its extent from Dirac's theory."

“Whether of not we would be able to observe it would, of course, depend on the intensity of the mutual perturbations. But by all means calculate the effect. Perhaps experimental physicists will then discover ways and means of corroborating your results.”

“I really think this whole ‘as if’ philosophy is terribly odd. The light quantum is said to behave in some experiments as if it consisted of an electron and a positron. But at other times it apparently behaves as if it consisted of two or more such pairs. The result is a wishy-washy kind of physics. And yet we can use Dirac’s theory to calculate the probability of a certain event with great precision, and find that experiments will confirm the results.”

...

Meanwhile Euler, together with another of my pupils, B. Kockel, determined the scattering of light by light, and although no experimental verification was possible here, there is little doubt today that the scattering effect they deduced is a fact.”

Appendix F

Extract from a letter of September 27, 1935 from W. Pauli to V. Weisskopf (Reprinted as letter [421a] in [245], pp. 769-771, specifically p. 770. English transl.: K.S.. The English translation is appended after the original German text.):

“...Pryce^[...] und ich haben beschlossen, wenigstens zu versuchen, die Häufigkeit des Streuprozesses zweier Lichtquanten aneinander *ohne* die Euler-Kockelsche Einschränkung hinsichtlich Kleinheit der Lichtfrequenzen gegen mc^2/h auszurechnen.

Ich bin mir darüber klar, daß das Problem nicht leicht ist. Nicht nur sind die auftretenden Integrale von einem komplizierteren Typus als das erwähnte Heisenberg-Serbersche Integral, sondern vor allem bekommt man zunächst die praktisch unendlich große Zahl von $6 \times 24 = 144$ Termen (nach Euler-Kockel). Dennoch scheint mir das Problem nicht so ganz hoffnungslos zu sein. Ich habe den Eindruck, daß die riesigen Koeffiziententabellen von Euler-Kockel nicht so sehr dem Subtraktionsformalismus als solchem zur Last zu legen sind als vielmehr dem Umstand, daß viel zu früh nach den g 's entwickelt wurde. Letzteres scheint mir nicht nur in formaler Hinsicht ungeschickt, sondern es wird auch in physikalischer Hinsicht durch die Beschränkung auf kleine v auch die Ähnlichkeit mit der Bornschen Theorie^{3[K.S.: orig. footn.]} vorgetäuscht; aber diese liefert keine Paarerzeugung! Das ist so wie wenn man eine Theorie hätte, die (für lange Wellen) Dispersion liefert, aber keine Absorption! Nach meiner Meinung haben Euler und Kockel in ihrer publizierten Note^{4[K.S.: orig. footn.]} ein viel zu starkes Gewicht gelegt auf den Vergleich mit diesem Ungetüm von einer Pseudothorie!

Nun aber zurück zur mathematischen Seite des Problems. Was mir eine gewisse Hoffnung gibt, durchzukommen ist der Umstand, daß das Problem sich sehr vereinfachen läßt durch Einführung eines speziellen Bezugssystems. Abgesehen von dem singulären Sonderfall, daß die beiden Lichtquanten im Anfangszustand exakt in derselben Richtung laufen (in welchem Sonderfall aus Ihnen sehr bekannten Gründen die Streuwahrscheinlichkeit ohnehin exakt verschwinden dürfte), kann man immer ein Bezugssystem einführen, wo $g_1 + g_2 = 0$ (d. h. die Lichtquanten laufen in entgegengesetzter Richtung aufeinander zu und ihre Frequenzen sind gleich). Und in diesem Normalkoordinatensystem werden die Formeln viel einfacher. Vielleicht gelingt es da, die Zahl 6×24 der Terme so weit zu reduzieren, daß man die Streuwahrscheinlichkeit wirklich ausrechnen kann (für beliebige Frequenz der Lichtquanten). – Zunächst rechnet Pryce allgemein die Spur aus (womit er fast fertig ist) und dann werden wir weiter sehen, ob wir durchkommen. Princeton ist ein Ort, der sehr geeignet ist, um komplizierte Integrale auszurechnen. ...”

English translation:

“...Pryce^[...] and I have decided to at least try to calculate the probability of the scattering process of two quanta of light off each other *without* the Euler-Kockel

³[K.S.: orig. footn.] Vgl. Born und Infeld (1934). (K.S.: cf. [30])

⁴[K.S.: orig. footn.] Euler und Kockel (1934). (K.S.: cf. [47])

restriction with respect to the smallness of the light frequency in comparison with mc^2/h .

I am aware of the fact that the problem is not an easy one. Not only the integrals occurring are of a more complicated type than the Heisenberg-Serber integral mentioned but primarily one gets the practically infinitely large number of $6 \times 24 = 144$ terms (according to Euler-Kockel). Despite this it seems to me that the problem is not that hopeless. It is my impression that the huge coefficient tables of Euler-Kockel are not that much due to the subtraction formalism as such as rather due to the problem that much too early an expansion in the g 's has been applied. To me, the latter does not only seem to be awkward but also in physical respect by virtue of the restriction to small v a similarity to the Born theory³[*K.S.: orig. footn.*] is being pretended to exist; but it does not yield any pair creation! This is the same as if one would have a theory that (for long waves) yields dispersion but not any absorption! In my view, in their published note⁴[*K.S.: orig. footn.*] Euler and Kockel have put much to strong emphasis on the comparison with this monstrosity of a pseudo-theory.

But now back to the mathematical side of the problem. What provides me with some hope to get through is the fact that the problem can considerably be simplified by introducing a special reference system. Disregarding the singular special case that two quanta of light in the initial state propagate in exactly the same direction (in which special case for reasons very well known to you the scattering probability should vanish exactly anyway), one can always introduce a reference system where $g_1 + g_2 = 0$ (i.e., the quanta of light propagate in directions opposite to each other and their frequencies are the same). And in this system of normal coordinates the formulas are becoming much easier. Perhaps one can succeed in reducing the number 6×24 of terms that much that one can really calculate the scattering probability (for arbitrary frequency of the quanta of light). – First Pryce calculates the trace in general (what he almost is done with) and then we will see further if we get through. Princeton is a place which is very much suited for calculating complicated integrals. ...”

³[*K.S.: orig. footn.*] K.S.: see footnote 3 on page 54.

⁴[*K.S.: orig. footn.*] K.S.: see footnote 4 on page 54.

Appendix G

Historic recollections by V. F. Weisskopf related to the articles [82, 100] (The passages are quoted from [258] with kind permission of the American Institute of Physics.):

“**Weisskopf:** ... Now I come to the work about the vacuum polarization, which I published in the Danish Academy^[hh]^[footn. K.S.]. I very rarely complain about not getting enough recognition because I think I’ve received in my life more recognition than I really deserved, but for this paper I don’t get enough recognition. In my opinion, this paper is really the beginning of re-normalization; and when you read it you’ll find, it. The first purpose of the work, and the one for which it is perhaps best known, was the recalculation in a very much simpler way of the Euler-Heisenberg vacuum polarization for slowly varying fields, which Wick mentioned today. It was really only a recalculation, although with very nice methods suggested by Pauli. This is why I didn’t publish it in *Zeitschrift für Physik*; I thought I should have something in the Danish Academy, and so I published this there because it was really only a simplification.

However, this same paper contains a study in which I was not very sure of myself, which is also why I published it in the Danish Academy, but which excited me very, very much. The study was to show that all the infinities that come about in calculation are in fact infinities that you cannot measure, namely, infinities of charge, infinities of mass, and infinities of what I called there the “dielectric constant of the vacuum.” As it says there explicitly, one could assume that the total result is given by nature and one can forget about these infinities. What is given there is the recipe for re-normalization. Again I say that if I had had my Sommerfeld training I could have done much more with this. In fact I used rather primitive methods there to prove my point and perhaps that is another reason that the work was not too well known. But you could directly quote from there a recipe for re-normalization. There is a paper by Dirac in which he says the same thing for the mass, I think, but I knew that already. I directly say there are three magnitudes which are essentially nowadays the three “Z’s”, the three infinities; and I say in there that these are the three infinities; but is characteristic that were they finite, you wouldn’t be able to notice them.

This is why you can forget them, and I say this explicitly in this paper. I did this work rather independently; Pauli was of course interested in it and he advised me in many things. By the way, I was always a sloppy man, and this paper was one that has the greatest number of calculating mistakes of any paper ever written; it’s terrific what’s wrong in there, but in principle it was right. ...

...

Heilbron: There’s just one paper, isn’t there, in the Danish Academy?

^[hh]K.S.: see ref. [100].

Kuhn: Let's get that chronology right on the tape now.

Weisskopf: The papers are, in order, as follows: '34, the self energy paper ordered by Pauli^[ii]^[footn. K.S.]; then the boson paper, the Klein-Gordon equation with Pauli^[ij]^[footn. K.S.]; and in '36, the polarization of the vacuum and the renormalization proposal^[kk]^[footn. K.S.], which was done partially with Pauli but was really written in Copenhagen. That's why it was published here.

...

Weisskopf: ... I did another paper with Kemmer on the scattering of light by light. I think this was in a letter to Nature^[ll]^[footn. K.S.]. We connected the scattering of light by light with the Delbrück scattering. Today it's a triviality; one light quantum is replaced by the Coulomb field, but at that time it was not so trivial. That thing was in fact the beginning of this later paper on the vacuum polarization where very similar problems are treated. That just shows that these were the things one was worrying about. No, I know what it was about; it had deeper significance, that letter to the editor. Euler and Kockel at that time, under Heisenberg, calculated the scattering of light by light, but had to do a lot of subtracting because there were a great many terms that were infinite. They did this in the usual clever way and got the result. And Kemmer and I showed that you can do the calculation without raking any subtractions, because you can show that it is equivalent to the Delbrück scattering, replacing one light quantum by the Coulomb field, and the Delbrück scattering doesn't diverge. This is a special case of what one does now every day if one calculates these things. ... ”

^[ii]K.S.: see ref. [259].

^[ij]K.S.: see ref. [261].

^[kk]K.S.: see ref. [100].

^[ll]K.S.: see ref. [82].

Appendix H

Historic recollections by N. Kemmer [263], pp. 171-172 (English transl.: K.S.. The English translation is appended after the original German text.):

“Weißkopf war damals auch in Zürich und arbeitete am Selbstenergieproblem in diesem neuen Rahmen^[mm]^[footn. K.S.]. Er fand, daß die neue Theorie immer noch an Divergenzen litt, die aber nur schwach (logarithmisch) waren [11]^[nn]^[footn. K.S.]. Ich beteiligte mich ein wenig an diesen Rechnungen und erlebte es mit, als Nachricht von Heisenberg ankam, daß zwei seiner Schüler, Euler und Kockel, aufgrund dieser Theorie die „Streuung von Licht an Licht“ berechnet hatten [12]^[oo]^[footn. K.S.]. Dies war ein wohldefinierter, kleiner, aber im Prinzip beobachtbarer Effekt, der als Abweichung von den Maxwell’schen Gleichungen beschrieben werden konnte. Die Autoren mußten bis zur vierten Ordnung in der Störungstheorie rechnen und ohne vollständige Rechtfertigung gewisse divergente Integrale vernachlässigen. Die Berechnung war enorm lang, obwohl sie nur für einige Spezialfälle durchgeführt wurde. Heisenberg war aber überzeugt, daß trotz der Unvollkommenheit der Theorie das Endresultat relativistisch invariant sein müsse. Unter dieser Annahme konnten Euler und Kockel ihr Ergebnis in der Form eines Zusatzes zur Lagrange-Funktion des Maxwell-Feldes angeben

$$L = \frac{1}{8\pi} (E^2 - B^2) + \frac{C}{360\pi^2} \left[(E^2 - B^2)^2 + 7 (\vec{E}\vec{B})^2 \right] \quad (2)$$

(in den damals üblichen Einheiten), wo

$$C = \left(\frac{e^2}{\hbar c} \right)^2 \cdot \left(\frac{\hbar}{mc} \right)^3 \cdot \frac{1}{mc^2} .$$

Unter Weißkopfs Leitung und mit Dr. Guido Ludwig als Mitarbeiter berechnete ich einen verwandten Effekt [13]^[pp]^[footn. K.S.], nämlich die (Delbrück-) Streuung von Licht an einem elektrostatischen Potential. In der Abwesenheit invarianter Rechenmethoden war es nicht offensichtlich, daß unser Resultat mit dem Euler-Kockelschen übereinstimmen würde. Ich fand aber genau dieselben Koeffizienten wie in (2). So lernte ich, daß man Invarianzargumenten trauen konnte – auch für eine ganz unvollkommene Theorie!”

^[mm]K.S.: i.e., hole theory, electron-positron theory [263], p. 171.

^[nn]K.S.: Reference in the original article [263]: [11] *Weisskopf, V.*, Z. Phys. **98**, 27 (1934), Berichtigung [correction] **90**, 817 (1934). (K.S.: cf. our ref. [259])

^[oo]K.S.: Reference in the original article [263]: [12] *Euler, H.*, u. *B. Kockel*, Naturwissenschaften **23**, 246 (1935). (K.S.: cf. our ref. [47]. For the letters of W. Heisenberg to W. Pauli reporting about the progress of this calculation see letter [374], pp. 331-333, and letter [393], pp. 358-360, in [214].)

^[pp]K.S.: Reference in the original article [263]: [13] *Kemmer, N.*, Helv. Phys. Acta **10**, 112 (1937) u. *G. Ludwig*, Helv. Phys. Acta **10**, 182 (1937). (K.S.: cf. our refs. [114, 115].)

English translation:

“At that time, Weiskopf also stayed in Zurich and worked on the self-energy problem within this new framework^[qq]^[footn. K.S.]. He discovered that the new theory still suffered from divergencies, however weak (logarithmic) ones [11]^[rr]^[footn. K.S.]. I took some part in these calculations and witnessed when news from Heisenberg arrived that two of his students, Euler and Kockel, had calculated the “scattering of light by light” on the basis of this theory [12]^[ss]^[footn. K.S.]. This was a well-defined, small, but observable in principle effect which could be described as a deviation from the Maxwell equations. The authors had to perform calculations up to the fourth order of perturbation theory and to neglect certain integrals without complete justification for doing so. The calculation was enormously long although it was done for some special cases only. However, Heisenberg was convinced that the final result had to be relativistically invariant despite the imperfection of the theory. Relying on this assumption, Euler and Kockel could present their result in terms of an addition to the Lagrange function of the Maxwell field

$$L = \frac{1}{8\pi} (E^2 - B^2) + \frac{C}{360\pi^2} \left[(E^2 - B^2)^2 + 7 (\vec{E}\vec{B})^2 \right] \quad (2)$$

(in the units customary then) where

$$C = \left(\frac{e^2}{\hbar c} \right)^2 \cdot \left(\frac{\hbar}{mc} \right)^3 \cdot \frac{1}{mc^2} .$$

Under the guidance of Weiskopf and with Dr. Guido Ludwig as collaborator I calculated a related effect [13]^[tt]^[footn. K.S.], namely the (Delbrück-) scattering of light by an electrostatic potential. In the absence of invariant calculational methods it was not obvious that our result would agree with the one by Euler-Kockel. However, I obtained the same coefficients as in (2). This way I learned that one can trust invariance arguments – also for a fairly imperfect theory!”

^[qq]K.S.: see footnote [\[mm\]](#) on page 58.

^[rr]K.S.: see footnote [\[nn\]](#) on page 58.

^[ss]K.S.: see footnote [\[oo\]](#) on page 58.

^[tt]K.S.: see footnote [\[pp\]](#) on page 58.

Appendix I

Historic recollections by A. I. Akhiezer about his kand. diss. (Ph.D. Thesis) research leading to the publications [64], [101] (The following passage is quoted from [264], pp. 36-38; for a somewhat shorter version also see [265], pp. 107-109, pp. 77-78 of the English translation.):

“Photon-photon scattering

Alter I passed the *theorminimum* Landau gave me a research subject. I was to study the scattering of light by light. Landau had earlier given this subject to Rosenkevitch, who was another of his students. He and Landau were going to investigate the scattering of light by light in the low-frequency domain, where the photon energy is much less than the mass of the electron. (Electron-positron pair production makes the electron mass an important parameter here.) But Rosenkevitch failed to solve this problem, and besides, there soon appeared a remarkable paper by Werner Heisenberg and his student Hans Euler that gave a complete solution. Landau was upset that the problem “got away” from him.

That happened just when I was passing the *theorminimum*. So Landau decided to test my abilities with this difficult problem of photon-photon scattering, but this time in the high-frequency domain where the photon energy exceeds the electron mass. The phenomenon in question was a fourth-order effect in perturbation theory. To calculate the scattering probability in that approximation, one should really use Dirac’s relativistic theory of the electron. But at that time, perturbation theory had been worked out only in nonrelativistic quantum mechanics. It was a hard task to calculate the scattering amplitude, because one had to take into account numerous intermediate states without overlooking any.

Eventually I had the amplitude written down and showed it to Landau. And that’s when the first, and last, blowup in my relations with Landau erupted. He didn’t like the nonrelativistic form of the probability amplitude. Besides, it was written in terms of photon vector potentials rather than the electromagnetic fields themselves. Therefore the expression was not gauge invariant. So Landau started getting angry, but he couldn’t make my expression relativistically and gauge invariant either. Nonetheless I strongly objected to his assertion that it couldn’t be done within the existing perturbation theory.

This conversation had become rather unpleasant by the time Rosenkevitch came in. Sizing up the situation, Rosenkevitch took two candlesticks standing on the desk, gave one to me and the other to Landau, and said, “Now fight it out.” Landau burst out laughing and said: “The hell with you. Do the calculations the way you want.” I understood that he couldn’t deny my general formula. So I decided that since the formula was correct, it should lead eventually to a properly invariant expression.

‘The best gammists’

It was then that Pomeranchuk began to work with me. The calculations were horrifying exercises in the manipulation of gamma matrices. Evgenii Lifshitz, coauthor of the famous Landau textbooks, joked that Pomeranchuk and I were “the best gammists in the Soviet Union.” (The joke, which loses something in translation, depends on the similarity of “gamma” to an indecorous Russian word for excrement.)

Landau was insistent that we check the gauge invariance of our result. To that end we replaced the vector potential with the field itself. We got 144 terms, which had to sum to zero. Chuk (that’s what we used to call Pomeranchuk) and I held our breaths as we did the sum. I can’t remember any other moment when I’ve been as happy as I was when I finally saw that the sum did indeed vanish. We immediately ran to Landau. He was happy too. Soon we had completed the calculation, getting a relativistically invariant expression for the scattering cross section in the high-frequency domain. We also succeeded in removing possible divergences simply by exploiting the gauge invariance of the amplitude.

We described our work to Victor Weisskopf, who had recently arrived in Kharkov. He was very pleased with it. At Landau’s seminar Weisskopf reported on his own work on the nonlinear electrodynamics of the vacuum, and he gave me the galley proofs of his paper. Though he obtained the same result Heisenberg and Euler had gotten earlier, Weisskopf’s method was beautiful. Landau was full of praise.

Landau suggested that we publish our results in the British journal *Nature*. Pomeranchuk and I wrote a brief paper, and Fritz Houtermans, a German émigré at our institute, promptly translated it into English. (For more on the peripatetic Houtermans see the letter by Victor Frenkel on page 104 and the article by Iosif Khriplovich in *PHYSICS TODAY*, July 1992, page 29.) Without bothering to get official permission, we took the article to the post office, and soon it was published under our three names.

Then Pomeranchuk and I concerned ourselves with the problem of the coherent scattering of gamma rays in the Coulomb field of the nucleus. This was another problem to be solved in the framework of Dirac theory. In 1937 there was a nuclear physics conference in Moscow. Pauli came, and Landau introduced Pomeranchuk and me to him. We familiarized Pauli with our work on light-light scattering and gamma scattering off nuclei. He approved. It was all a brilliant success for Landau’s “school,” because it indicated that we were dealing with the most important theoretical problems of the day.”

Appendix J

Historic recollections by László Tisza (MIT, Cambridge, MA, USA) about the kand. diss. (Ph.D. Thesis) research by A. I. Akhiezer leading to the publications [64], [101] (The following passage is quoted from [266], pp. 307-308.):

“III. SCATTERING OF LIGHT BY LIGHT

P. A. M. Dirac published in 1928 a remarkable paper in which he established a relativistically invariant form for quantum mechanics. This theory was at first plagued by a curious difficulty, it called for negative energy states for the electron. Dirac later showed that instead of reversing the sign of the energy, one might reverse the sign of its charge. At first this did not improve the situation much until the discovery of the positron in 1932 changed the difficulty into a most remarkable prediction of any theory. The use of the Dirac equation still was not obvious. The 4×4 gamma matrices involved in this equation made manipulations difficult. There was an International Theoretical Conference in May 1934 at the UFTI^[uu]^[footn. K.S.] where these questions were discussed. By 1935 pair production problems were rather standard although they remained labor-intensive.

Shura^[vv]^[footn. K.S.] and myself completed about the same time our theoretical minimum. We turned to Landau to start us off in research. The Dirac perturbation theory was ready for use, mainly as a result of the so-called Casimir method for handling gamma matrices; we all started along this line. Shura got the assignment of the «scattering of light by light». This was a very difficult problem of fourth-order perturbation calculus. After a while he and Chuk^[ww]^[footn. K.S.] decided to join forces. This was a fortunate decision. I vividly remember the two sitting side by side at two desks, working through long sequences of calculations. They were doing the same step independently and proceeded to the next step only after their results checked. They reminded me of the famous cartoon characters: Max and Moritz by Wilhelm Busch, two mischievous boys, one of them with a funny hairdo. This one was clearly Chuk. He was always full of ideas, be it something funny, or some important physics. Landau said that Chuk reminded him of his younger self. They had both striking ironical faces, but Dau^[xx]^[footn. K.S.] was tall and Chuk was short and boyish. Shura has his own benign sense of humor. The two were sitting at their desks, constantly joking and cursing while doing their ghastly calculations.

Eventually they finished and convinced Dau that all was right. (See Akhiezer’s paper in *Physics Today*^[yy]^[footn. K.S.] of 1994.) At the time the foremost expert Victor Weisskopf was visiting and he endorsed the work as well. When the secretary received the manuscript for typing, the title «Scattering of light by light» provoked

^[uu]K.S.: UFTI = Ukrainian Physico-Technical Institute.

^[vv]K.S.: Shura = A. I. Akhiezer.

^[ww]K.S.: Chuk = I. Ya. Pomeranchuk.

^[xx]K.S.: Dau = L. D. Landau.

^[yy]K.S.: see ref. [264] (and our App. I).

her perceptive remark: «do chevo zhe dumalis!» In free translation: «What will they dream up next?»

His hard work paid off, Akhiezer passed his grueling test to be ready to become Landau's successor in due time.”

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[For references in Cyrillic letters, we apply the (new) *Mathematical Reviews* transliteration (transcription) scheme (to be found at the end of index issues of *Mathematical Reviews*). Georgian references are transliterated on the basis of ISO 9984. Chinese references are transcribed using Hanyu Pinyin with tone marks. For Japanese references the modified Hepburn transcription system is used. Arabic and Persian references are romanized using the ALA-LC standard.]

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