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A Classical Model for Wave-Particle Duality

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A model of de Broglie waves, based on the hypothesised existence of zero-point electromagnetic background radiation, is presented. Based on this model a brief review of a paradigm for quantum mechanics is presented. Bell's Theorem is examined and reinterpreted so as to preclude its negative consequences. Finally, a possibly observable effect suggested by this model pertaining to the coherence length of particle beams is considered.

INTRODUCTION

Wave-particle duality and its attendant philosophical principle of complementarity is perhaps the most well known, counter intuitive concept introduced by the discipline of physics. Unlike virtually every other basic notion originating with the physical sciences, this principle is distinguished by its ambiguity and preternatural character. As such it has had a particular attraction to those put off by the stolid nature of conventional science. Nevertheless, because of its vague logic, duality is also a source of discomfort for those abhorring imprecision or 'spookiness' in physical science.

The purpose of this presentation is to describe a model using concepts from classical physics for wave-particle duality. [1] The basis of this model is the electromagnetic zero-point background whose existence is the foundation of the theory of Stochastic Electrodynamics (SED). [2] It will be argued below that the existence of such a zero-point background engenders the properties observed for waves and particles that gives each characteristics of the behaviour of the other in certain limiting circumstances.

Although a unified concept, wave-particles clearly can be distinguished into two categories: entities whose classical, large scale limit is wavelike (e.g., photons) and entities whose classical limit is particle-like (e.g., electrons, atoms, etc.). In both cases the zero-point field, it will be argued herein, has the effect of introducing the surprising aspect heretofore attributed to ontological duality.

PARTICULATE BEHAVIOUR OF ELECTROMAGNETIC WAVES

From the viewpoint of SED, electrodynamics signals are classical waves whose fluctuations obey what is often called 'photon statistics.' It is the contention herein that the literal concept of a photon is superfluous because observable manifestations attributed to their existence can be accounted for by waves which obey photon statistics.

The essential feature of zero-point background radiation is determined by the requirement that its spectral energy density $E(\omega)$ be invariant under Lorentz transformations in the sense that the total energy between two fixed numerical values of ω, a and b, be identical in all inertial frames; *i.e.*,

$$\int_a^b E(\omega)\, d^3k = \int_a^b E'(\omega)\,\gamma(1-v/c)d^3k, \tag{1}$$

$\left[\gamma \equiv (1-v^2/c^2)^{-1/2}\right]$. As Physics, this stipulation is tantamount to the requirement that there be no distinguishable frames; and, it is based on the fact that, were it not true, the background would engender certain anisotropisms that in fact are not observed.

Eq. (1) is satisfied by a linear spectral energy density $E(\omega) = \text{constant} \times \omega$ where the constant scale factor is determined empirically to be Planck's constant$/4\pi$—$\hbar/2$. [2, 3]

The essence of photon statistics and the Planck blackbody spectrum can be found by manipulation the following four equations involving the mean energy density $\overline{E_i}$, the mean square energy density $\overline{E_i^2}$, and the mean square deviation of the energy density $\overline{(\delta E_i)^2}$ of any two mutually incoherent radiation fields:

$$\overline{E_{\text{sum}}} = \overline{E_1} + \overline{E_2}, \tag{2}$$

$$\overline{E_1 E_2} = \overline{E_1}\,\overline{E_2}, \tag{3}$$

$$\overline{(\delta E)^2_{\text{sum}}} = \overline{(\delta E_1)^2} + \overline{(\delta E_2)^2} \tag{4}$$

and

$$\overline{(\delta E_i)^2} = \overline{E_i^2} - \overline{E_i}^2 = \overline{E_i}^2; \qquad i = 1,2 \tag{5}$$

to obtain

$$\overline{(\delta E_{\text{T}})^2} = \overline{E_{\text{T}}^2} + 2\overline{E_{\text{T}}}\,\overline{E_{\text{B}}} \tag{6}$$

where, in the case at hand, $\overline{E_{\text{B}}}$ is the mean energy density solely of the background radiation, and $\overline{E_{\text{T}}}$ is the same for a temperature dependant radiation field. This latter field coexists with the background and is modified by it via the mutual interference terms which are included in E_{T}. Invoking the Fluctuation Theorem

$$\partial\overline{E_{\mathrm{T}}}/\partial\mu = \overline{(\delta E_{\mathrm{T}})^2}, \tag{7}$$

$[\mu \equiv -1/kT]$, for the thermal field at temperature T where k is Boltzmann's constant, yields the differential equation

$$\partial\overline{E_{\mathrm{T}}}/\partial\mu = \overline{E_{\mathrm{T}}}^2 + 2\overline{E_{\mathrm{B}}}\,\overline{E_{\mathrm{T}}}, \tag{8}$$

whose solution, with $\overline{E_{\mathrm{B}}} = \hbar\omega/2$, is the Planck blackbody spectral energy distribution

$$\overline{E_{\mathrm{T}}} = \frac{\hbar\omega}{e^{\hbar\omega/kT} - 1}. \tag{9}$$

Eq. (6) written in the form

$$\frac{\overline{(\delta E_{\mathrm{T}})^2}}{\overline{E_{\mathrm{T}}}^2} = 1 + 2\frac{\overline{E_{\mathrm{B}}}}{\overline{E_{\mathrm{T}}}} \tag{10}$$

elucidates the source of the dualistic nature of radiation. [3] Were the first term on the right to stand alone, Eq. (10) would characterise intensity fluctuations of a classical radiation field, while the second term alone, being proportional to $1/\overline{E_{\mathrm{T}}}$, gives an equation characterising density fluctuations of a particle ensemble. Together they capture the essence of photon statistics and thus, without assuming the existence of discrete quanta, characterise the 'quantised electromagnetic field.' [3]

The point here is that the fluctuation statistics observed at very low densities in anti-correlation experiments, and taken to demonstrate the particle nature of photons, can be explained as well as a consequence of the existence of zero-point radiation.

WAVE BEHAVIOUR OF PARTICLES

All particles with charge structure are considered to be in thermodynamic equilibrium with the zero-point background via interaction with signals at frequencies characteristic of their structure. The model for wavelike behaviour of particles is based on the *Ansatz* that, in frames in which they are moving, particles will be deflected by diffraction patterns in the background signals to which they are tuned. Background waves, being conventional electromagnetic radiation, are diffracted by physical boundaries according to the usual principles of optics. For example, a particle moving towards a slit would equilibrate with a signal that is a standing wave in its own frame but which is a travelling wave in the slit's frame where it diffracts at boundaries such as those of a slit. On passage through a slit, a particle is subject to the lateral energy flux attendant to the diffraction pattern of the background signal to which it is tuned. In other words, it is envisioned that a particle will tend to be jostled into the energy nodes of the diffraction pattern of the "standing wave" to which it is tuned in its own inertial frame, but which is a translating wave in the frame of the slit. This effect is similar to the way froth and debris tend to track the nodes of standing waves in rivers or sand tends to settle on the nodes of a vibrating membrane. An ensemble of similar particles in identical circumstances—*e.g.*, a beam of particles impinging on a slit—upon accumulation at the detector discloses the diffraction pattern of the composite wave comprised of components with which the individual particles are in equilibrium.

Consider, for example, a neutral particle or system consisting of a dipole of opposite charges held apart by some internal structure modelled to first order by a simple spring with resonant frequency ω_0. According to the basic SED assumption of thermodynamic equilibrium with the background, the rest energy of this system constituting the particle will equal the energy in the background mode ω_0, which is also the resonant frequency of the system at which it is exchanging energy with the background; that is

$$m_0 c^2 = \hbar\omega_0, \tag{11}$$

where a contribution of $\hbar\omega_0/2$ is made to the right side by both polarisation states of the background mode. (For systems with more complex internal structure, ω_0 stands for the sum of the frequencies corresponding to the various possible interactions.) In its rest frame, with respect to each independent spatial direction, on the average a particle will tune into and equilibrate with those background signals constituting a standing wave having an antinode at its location, which, if the particle is located at $x = 0$, has an intensity proportional to the expression $2\cos(k_0 x)\sin(\omega_0 t)$. When projected onto a coordinate frame translating at velocity v with respect to the particle, that of a slit for example, this standing wave has the form of the modulated translating wave and is proportional to

$$2\cos(k_0\gamma(x - c\beta t))\sin\left(\omega_0\gamma\left(t - c^{-1}\beta x\right)\right), \tag{12}$$

where $[\beta \equiv v/c]$.

This wave consists of a short wavelength carrier modulated at a wavelength $\lambda = (\gamma\beta k_0)^{-1}$ inversely proportional to the relative velocity of the particle with respect to the slit. The modulation on this wave is a relativistic kinematic effect. It arises from the difference in the Lorentz transformed form of the oppositely translating components of a standing wave.

The modulated wave, upon propagation through a slit, for example, is diffracted according to Huygens' Principle such that the modulation diffraction pattern is imposed on the carrier's diffraction pattern. A particle bathed in this diffracted wave will experience a gross energy flux with a spatial pattern proportional to the square of the modulation intensity imposed on the fine-scale background wave driving the *Zitterbewegung*. In other words, according to this interpretation, boundary conditions on background zero-point waves modify the stochastic effects of *Zitterbewegung* on the orbits of material particles. The actual detailed motion of a particle, while it reflects the relatively large scale effects of the modulation, is very complex and jitters in consort with spatially modulated *Zitterbewegung*.

Now, a Lorentz transformation into the translating frame applied to both sides of the statement of energy equilibrium, Eq. (11), yields both

$$\gamma m_0 c^2 = \gamma\hbar\omega_0, \tag{13}$$

and

$$p' = \gamma m_0 c = \hbar\gamma\beta k_0\,. \tag{14}$$

From Eq. (14), $\gamma\beta k_0$ can be identified as the De Broglie wave vector from conventional QM.

Within this conceptual framework, the interpretational contradictions or ambiguities that arise in conventional QM with respect to duality are simply precluded from the start. Here particles are particles and waves are waves although each is induced by the zero-point background to exhibit certain behaviour in the microdomain reminiscent of the other. Particles are the primitive elements of this theory whose existence is assumed axiomatically. Waves are mathematical constructs representing Fourier components of a decomposition of interactions occurring via action-at-a-distance on the light cone (i.e., free electromagnetic fields without sources are regarded as artifacts of convenience). The purpose of the theory is to describe the motion of particles given *a priori* interacting via electromagnetism in the presence of zero-point radiation. The zero-point radiation itself is assumed to originate from those remaining charges in the universe excluded from immediate interest. [1]

QUANTUM THEORY

The physical model of a background wave so affecting a particle's trajectory that it assumes a ray-like character also provides an novel understanding of the physical significance of the Schrödinger Equation and its solutions. The basic idea here is that the energy density of the zero-point wave with which a particle is in equilibrium is a wave with half the wavelength of its supporting zero-point wave and this energy density pattern is effectively an agent inducing ray-like characteristics in particle trajectories. Thus, if one considers a Gibbsian ensemble of similar particles with density $\rho(x,p,t)$, then the ensemble wave will be the Fourier composite over the variation in momentum of the ensemble.

Consider a particle subject to a force $\mathbf{F}$ and for which the density of trajectories on phase space is $\rho(x,p,t)$, where $\rho(x,p,t=0)$ can be regarded either as the distribution of initial conditions for similarly prepared particles, or, equivalently, as the *a prior* probability distribution of initial conditions for a single particle. Time evolution of $\rho(x,p,t)$ is governed by the Liouville Equation

$$\frac{\partial\rho}{\partial t} = -\nabla\rho\cdot\frac{p}{m} + (\nabla_p\rho)\cdot\mathbf{F}\,, \qquad \left[\nabla_p \equiv \sum_{i=x,y,z}\frac{\partial}{\partial p_i}\right]. \tag{15}$$

By virtue of Eq. (14), each value of p in $\rho(x,p,t)$ is correlated with a particular wavelength of kinematical modulation. As proposed above, boundaries and geometrical constraints on the waves to which the particle is tuned cause these waves to diffract and interfere so that gradients in their energy densities are induced. These gradients, in turn, result in spatial variations in the magnitude of the *Zitterbewegung*, the average effect of which is to systematically modify particle trajectories. Because the energy density of a wave is proportional to the square of its intensity, the wavelength of energy density oscillations caused by the modulation will be half that of the modulation itself. That is, the wavelength of the physical agent modifying trajectories, an energy gradient, is half that of the modulation. Further, an ensemble consisting of multiple particles, either conceptual or extant, will be guided by an ensemble of energy density waves derived from an ensemble of kinematical modulations. The spatial structure of this ensemble wave is found by taking the Fourier transform of $\rho(x,p,t)$ with respect to $2p/\hbar$, the wave vector for the physical agent; *i.e.:*

$$\hat{\rho}\left(x,x',t\right) = \int e^{\frac{i2p\cdot x'}{\hbar}}\rho\left(x,p,t\right)\,dp\,, \tag{16}$$

for which the similarly transformed Liouville Equation is

$$\frac{\partial\hat{\rho}}{\partial t} = \left(\frac{\hbar}{i2m}\right)\nabla'\nabla\hat{\rho} - \left(\frac{i2}{\hbar}\right)\left(x'\cdot\mathbf{F}\right)\hat{\rho}\,. \tag{17}$$

Solutions for equations of this form are sought by first separating variables using a transformation of the form

$$r = x + x'\,, \qquad r' = x - x' \tag{18}$$

which yields

$$\begin{aligned}\frac{\partial\hat{\rho}}{\partial t} \;=\; &\left(\frac{\hbar}{i2m}\right)\left(\nabla^2 - \left(\nabla'\right)^2\right)\hat{\rho} \\ &- \left(\frac{i}{\hbar}\right)\left(r - r'\right)\cdot\mathbf{F}\left(\frac{r+r'}{2}\right)\hat{\rho}\,.\end{aligned} \tag{19}$$

In general, for an arbitrary form of the force $\mathbf{F}((r+r')/2)$, this equation still is not separable. However, for potentials having the form of a quadratic polynomial, the extraction the Schrödinger Equation follows directly. Non quadratic potentials, which include the important case of the coulomb potential, may still be includable with novel analysis. [1]

The logic of the extraction of the Schrödinger Equation given above, requires that physically realizable solutions be those for which the resulting phase space density is everywhere positive and such that $\rho(x,p,t=0)$ is the appropriate initial condition. The relationship between solutions satisfying these physics requirements and the eigenfunctions of the Schrödinger Equation is a complex question and is left for future study. However, it seems clearly auspicious in this regard, that thermal states; *i.e.*, mixed states with Boltzmann weighting factors, and coherent states give physically interpretable, everywhere positive densities as well as other desirable traits. [4].

BELL'S THEOREM

The above interpretation seems to achieve exactly what Bell's Theorem is believed to preclude, namely an interpretation of QM with a classical underpinning with implied 'hidden variables.' [5] Thus, a reconciliation is needed. To this end, note that Bell's analysis is comprised of two separate elements: a theorem and a question.

The theorem can be put as follows: *If* $\mathbf{A}(\mathbf{a},\lambda)$ *and* $\mathbf{B}(\mathbf{b},\lambda)$ *are dichotomic functions such that each is independent of the other and if* $\rho(\lambda)$ *is a normalised density over a parameter space represented by* λ*, then* **A** *and* **B** *satisfy Bell-type inequalities, in particular*

$$1+P(\mathbf{b},\mathbf{c}) \geq \mid P(\mathbf{a},\mathbf{b})-P(\mathbf{a},\mathbf{c}) \mid, \tag{20}$$

where

$$P(\mathbf{a},\mathbf{b}) \equiv \int d\lambda \rho(\lambda)\mathbf{A}(\mathbf{a},\lambda)\mathbf{B}(\mathbf{b},\lambda). \tag{21}$$

So much is mathematics. It is a rigorous result beyond any contest.

However, physics in Bell's analysis is embedded in the following question: For spin correlations in the Bohm version of Einstein-Podolsky-Rosen (EPR) experiments, are expressions of the sort given by Eq. (21) identical to the QM calculation expressed as:

$$<\sigma_1 \cdot \mathbf{a}, \sigma_2 \cdot \mathbf{b}> = -\mathbf{a} \cdot \mathbf{b} \tag{22}$$

where **a** and **b** are direction unit vectors with respect to which the spin measurements are made? [5]

The answer on the surface to this question is clearly 'no' as expression (22) does not satisfy the inequality (20). The reason behind this, however, is buried in the structure of QM rather than mathematics. But given the vague foundations of QM, the significance of this answer is open to any amount of contest.

In particular, Eq. (22) is interpreted ordinarily to be the cross-correlation of the results of individual spin measurements on the electrons in an EPR experiment. But, by definition, this correlation requires specific values from individual repetitions of the experiment and this information is in principle and fact not existent in QM. That is, the results of individual events can not be predicted with QM, only 'expectation values' can be computed. Thus, logic would seem to require that expression (22) can be actually only the correlation of expectation values rather than the correlation of individual events.

Because QM has neither an intuitive interpretation nor an axiomatic foundation, fixing precisely the meaning of expression (22) becomes a matter for argument. Those who find it easier to accept that mortals misconstrue things than that nature is nonlocal might elect heretically to view (22) as simply a variant expression of Malus's Law describing the intensity of polarised light with respect to an arbitrary axis. Such an interpretation eerily conforms with the fact that virtually all tests of Bell's inequalities have been optical experiments wherein polarisation is treated analogously to spin. [6] Moreover, actual dichotomic data fitting EPR conditions; i.e., raw sequences of plus- and minus-ones in equal quantities, can not be made to yield the sinusoidal correlation evidenced by Eq. (22) even if they are credited with non-locality, the inclusion of which is generally though to be QM's way around Bell's result. (This observation is a variation of Bell's Theorem; doubters are challenged to find a counter example.) The point is, the 'no' answer to Bell's question might be utterly natural because the QM side of the equation has been misinterpreted. In this case, Bell's arguments pose no fundamental impediment to constructing a hidden variable interpretation for QM. [7]

CONCLUSION

A new interpretation for QM, even if it has philosophical and pedagogical advantages, fails to meet the contemporary standard of science if it fails to predict an otherwise unexpected observable result. While such a prediction has yet to be made for the 'zero-point' interpretation of QM, perhaps the following preliminary notions will lead to a suitable experiment.

The coherence length of the de Broglie waves associated with particle beams is related to the velocity spread. According to the above model, *Zitterbewegung* will induce an irreducible minimum in the velocity spread. This, in turn, implies that there is an irreducible coherence length for a given type of particle beam. Now, if *Zitterbewegung* is induced, as supposed above, by a real electromagnetic zero-point field, then it seems natural that the zero-point field would be more effective; that is, impel larger *Zitter* excursions for ionised atomic beams than for neutral atomic beams which couple only by multipole interactions whose impulse is smaller. In other words, the intrinsic, irreducible coherence length for ionised beams should be larger than for neutral beams. In some manifestation, this effect ought to be observable.

As other interpretations for the nature of de Broglie waves do not imply a dependence on the ionisation state, the observance of such a dependence should constitute support for the interpretation espoused above.

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[7] Further details are to be found in: A. F. Kracklauer, unpublished manuscript (as yet).