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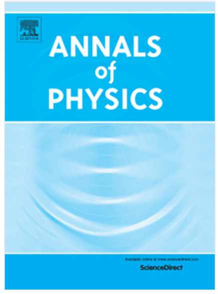

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Quantum phases for point-like charged particles and for electrically neutral dipoles in an electromagnetic field

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Abstract

We point out that the known quantum phases for an electric/magnetic dipole moving in an electromagnetic (EM) field must be presented as the superposition of more fundamental quantum phases emerging for elementary charges. Using this idea, we find two new fundamental quantum phases for point-like charges, next to the known electric and magnetic Aharonov-Bohm (A-B) phases, named by us as the complementary electric and magnetic phases, correspondingly. We further demonstrate that these new phases can indeed be derived via the Schrödinger equation for a particle in an EM field, where however the operator of momentum is re-defined via the replacement of the canonical momentum of particle by the sum of its mechanical momentum and interactional field momentum for a system "charged particle and a macroscopic source of EM field". The implications of the obtained results are discussed.

1. Introduction

To the end of past century, four quantum phase effects had been found, which are characterized correspondingly by the electric Aharonov-Bohm (A-B) phase [1]

$$\delta_\varphi = \frac{e}{\hbar}\int \varphi dt , \tag{1}$$

the magnetic A-B phase [1]

$$\delta_A = \frac{e}{\hbar c}\int \boldsymbol{A}\cdot d\boldsymbol{s} , \tag{2}$$

the Aharonov-Casher (A-C) phase [2]

$$\delta_{mE} = \frac{1}{\hbar c}\int \left(\boldsymbol{m}_0 \times \boldsymbol{E}\right)\cdot d\boldsymbol{s} , \tag{3}$$

and the He-McKellar-Wilkens (HMW) phase [3, 4]

$$\delta_{pB} = -\frac{1}{\hbar c}\int \left(\boldsymbol{p}_0 \times \boldsymbol{B}\right)\cdot d\boldsymbol{s} , \tag{4}$$

where $d\boldsymbol{s}=\boldsymbol{v}dt$ is the path element of a charged particle e, moving with the velocity $\boldsymbol{v}$.

The electric (1) and magnetic (2) A-B effects emerge for charged particle in the field of scalar potential φ and vector potential $\boldsymbol{A}$, correspondingly; the A-C phase (3) is associated with the hidden magnetic momentum [5-7] of a point-like magnetic dipole $\boldsymbol{m}_0$, moving in an electric field $\boldsymbol{E}$, while the HMW phase (4) is defined via the hidden electric momentum (according to the terminology introduced in refs. [8, 9]) of a point-like electric dipole $\boldsymbol{p}_0$, moving in a magnetic field $\boldsymbol{B}$. The vectors $\boldsymbol{m}_0$ and $\boldsymbol{p}_0$ are measured in the rest frame of a dipole, and hereinafter we adopt that the dipoles are electrically neutral.