Comment on "Röntgen Quantum Phase Shift: A Semiclassical Local Electrodynamical Effect?"

In a recent Letter on the quantum phase of the electric dipole moving near a straight line of magnetic charges, Horsley and Babiker (HB) [1] claim that the phase possesses a semiclassical origin, in the sense that it is due to the action of a nonvanishing force acting on the dipole. The discussion on the locality of quantum effects of the Aharonov-Bohm [2] type for the electric dipole is somewhat analogous to that of the magnetic dipole [3], relevant to the Aharonov-Casher effect. However, the electric dipole possesses a simple internal structure so that modifications of the force expression (such as that due to the *hidden momentum* [3]) are not present in the case of the electric dipole. HB consider the force $\mathbf{F}$ in the rest frame of the dipole and use the expression

$$\mathbf{F}_{\mathrm{HB}} = \nabla(\mathbf{d}\cdot\mathbf{E}), \tag{1}$$

where $\mathbf{d}$ is the electric dipole and $\mathbf{E}$ the external electric field. However, the universally accepted interaction Lagrangian of a charged point particle in the presence of the fields $\mathbf{E}$ and $\mathbf{B}$, $L_{\mathrm{int}} = -q\Phi + q\mathbf{v}\cdot\mathbf{A}$, leads to the force expression $\mathbf{F} = q\mathbf{E} + q\mathbf{v}\times\mathbf{B}$. The Lagrangian and force for the electric dipole, constructed from that of a charged particle, have been considered in Ref. [4]. The Lagrangian and force on a particle possessing both magnetic and electric dipole moments have been derived by Anandan [5]. For an electric dipole with fixed orientation ($\dot{\mathbf{d}} = 0$), the force on the dipole in its rest frame reads

$$\begin{aligned}\mathbf{F} &= (\mathbf{d}\cdot\nabla)\mathbf{E} = \nabla(\mathbf{d}\cdot\mathbf{E}) - \mathbf{d}\times(\nabla\times\mathbf{E})\\ &= \nabla(\mathbf{d}\cdot\mathbf{E}) + \mathbf{d}\times(c^{-1}\partial_t\mathbf{B}).\end{aligned} \tag{2}$$

Expression (2) coincides with the leading terms of the expressions of Refs. [4,5], written in the dipole rest frame. The correct force expression (2) differs from that of HB (1) by the time-dependent term $\mathbf{d}\times(c^{-1}\partial_t\mathbf{B})$ that does not vanish in our case. Thus, HB have used an incorrect expression for the force on the dipole, which is valid for time-independent fields only. For the magnetic charge distribution considered by HB, the dipole is oriented in the direction of the line of magnetic charges (the z direction) and the field $\mathbf{E}$ does not depend on z. Therefore, the correct force expression (2) yields $\mathbf{F} = d\partial_z\mathbf{E} = 0$, implying that there are no forces acting locally on the dipole.

HB assume that the quantum phase of an electric dipole is due to the Röntgen interaction term. However, other approaches also appear in the literature. For example, the quantum phase derived in Ref. [4] contains the Röntgen term but is more general than the sole Röntgen interaction and, for the magnetic charge distribution considered by HB, it leads to a null result [4,6]. Source distributions of fields and potentials that lead to a nonvanishing phase for the electric dipole are presented in Refs. [4,6]. In the case of the source distribution considered by Tkachuk [6], where the nonvanishing contribution to the phase is due to the Röntgen term only, the approaches of HB [1] and of Ref. [4] give the same result.

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