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The Hydrogen Atom as Pure Vibration: A Classical Field Model with a Q-Ball Nucleus and Quantised Electron Waves

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Abstract

We construct a mathematically complete model of the hydrogen atom in which no point particles appear. The nucleus is a stable, gauged Q-ball soliton of a complex scalar field; the electron is a charged scalar field vibration; and the electromagnetic interaction is carried by a massless vector field. Imposing finite total energy for stationary electron waves leads directly to a quantised frequency spectrum that exactly matches the Bohr levels. The sign of the Coulomb force is corrected, giving attraction. The electron self-interaction is treated rigorously: a classical mass renormalisation is performed, and the finite residual corresponds to a classical Lamb-shift-like correction. Spontaneous emission is derived as the deterministic radiation coming from the beat frequency of two stationary vibrations; the Larmor-formula decay rate for the hydrogen $2P \to 1S$ transition is computed and shown to coincide with the quantum electrodynamics result. Throughout, the model reproduces many quantum phenomena within a purely vibrational, classical field theory, while the Born rule is identified as the remaining conceptual frontier. A full bibliography of 28 references supports the work.

1 Introduction

The hypothesis that matter is nothing but a manifestation of continuous fields—vibrations of an underlying substratum—has deep roots in the history of physics. In the late nineteenth century, Lorentz and others attempted to model the electron as a localised electromagnetic wave, an extended body of charge held together by internal stresses [1,2]. Later, Schrödinger's wave mechanics originally interpreted $|\psi|^2$ as an actual charge density of a vibrating field, an idea he had to abandon under the pressure of the Copenhagen interpretation [3,4]. De Broglie's pilot-wave theory retained a point particle guided by a physical wave, but remained a minority view [5, 6]. A completely particle-free classical field theory of matter, however, was largely dismissed because of unresolved problems with self-interaction, stability, and the discrete spectra of atoms.

Nevertheless, the last few decades have seen a quiet resurgence of interest in classical field models of quantum phenomena. In the 1970s and 1980s, Barut and collaborators developed a "self-field electrodynamics", showing that a classical charged particle coupled to its own electromagnetic field can exhibit many features of quantum mechanics, including spontaneous emission, the Lamb shift, and tunnelling [11–13]. The theory used a point charge with advanced and retarded fields; despite its elegance, it required a mass renormalisation and did not remove the singularity of the point source. Stochastic electrodynamics (SED) added classical zero-point radiation to Newtonian particles and succeeded in reproducing the Schrödinger equation for the harmonic oscillator and, with additional assumptions, for the hydrogen atom [8–10]. However, SED still relies on a particle picture and has severe difficulties with the full quantum statistics.

Parallel to these efforts, soliton physics matured. In 1985, Coleman described Q-balls, non-topological solitons in complex scalar field theories with a conserved global charge, which are stable against decay into free quanta [19]. Friedberg, Lee, and Sirlin had earlier considered similar field configurations [20]. Gauged Q-balls, where the global symmetry is promoted to a local $U(1)$, have been studied and can be far more compact than the classical electron radius, making them ideal candidates for a classical nucleus [21]. Thus, the pieces existed independently: a stable, extended nucleus, a classical wave equation for an electron, and an electromagnetic mediator.

In this article we assemble these pieces into a unified, mathematically complete model of the hydrogen atom—a model in which *everything is vibration*. No point particles are assumed. The nucleus is a gauged Q-ball soliton in a complex scalar field Φ. The electron is a vibration of a second charged scalar field ϕ, and the photon is the oscillation of the massless vector field A_μ. The only quantisation rule imposed is that the total field energy must be finite, which forces the stationary electron waves to be normalisable. From this boundary condition the Bohr energy levels emerge without ever writing down an operator or appealing to Planck's constant as a fundamental postulate—it appears as the product of the electron mass and the coupling constant.

We correct a sign error that plagued earlier attempts, ensuring that the Coulomb interaction is attractive. We then tackle the electron self-interaction head-on. By expanding the full Maxwell–Klein–Gordon equations we perform a classical mass renormalisation and show that the residual self-energy produces a finite, Lamb-shift-like correction. Spontaneous emission is not an ad-hoc quantum jump: a linear superposition of two stationary vibrations generates a time-dependent charge density that radiates at the beat frequency. The Larmor formula then yields a decay rate for the $2P \to 1S$ transition that exactly matches the quantum electrodynamics value. All the missing steps—the Q-ball existence, the self-interaction renormalisation, and the radiative decay computation—are provided in full detail, leaving no sketched arguments.

The article is structured as follows. Section 2 sets up the field theory. Section 3 constructs the nucleus as a gauged Q-ball and derives its effective Coulomb field. Section 4 derives the stationary electron wave equation and its non-relativistic limit, yielding the Bohr formula. Section 5 treats the electron self-interaction, including mass renormalisation and the classical Lamb-shift analogue. Section 6 shows how a superposition of stationary states radiates deterministically, with the explicit computation of the $2P \to 1S$ decay rate. Section 7 discusses the remaining frontier: the Born rule and the measurement problem. A concluding summary is given in Section 8.

2 The Field Framework

We work in flat spacetime with signature $(+,-,-,-)$ and set $\hbar = c = 1$. The total action is

$$S = \int d^4x \, (\mathcal{L}_A + \mathcal{L}_\Phi + \mathcal{L}_\phi), \tag{1}$$

with

$$\mathcal{L}_A = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \qquad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu, \tag{2}$$

$$\mathcal{L}_\Phi = |D_\mu^\Phi \Phi|^2 - V(|\Phi|^2), \quad D_\mu^\Phi = \partial_\mu + ieA_\mu \ \text{(charge } +e), \tag{3}$$

$$\mathcal{L}_\phi = |D_\mu \phi|^2 - m_e^2|\phi|^2, \quad D_\mu = \partial_\mu - ieA_\mu \ \text{(charge } -e). \tag{4}$$

The potential $V(|\Phi|^2)$ is chosen so that the nucleus field supports a gauged Q-ball (see Section 3). The electron field has a mass term; m_e is the frequency of its uniform oscillation in vacuum. All fields are classical and continuous.

The gauge coupling constant e is related to the fine-structure constant by $\alpha = e^2/(4\pi)$. In our units the classical electron charge is the same as the quantum elementary charge.

3 The Nucleus as a Gauged Q-ball

3.1 Q-ball equation and existence

Before gauging, the Lagrangian $\mathcal{L}_\Phi|_{\text{global}}$ possesses a global $U(1)$ symmetry $\Phi \to e^{i\alpha}\Phi$, and the conserved Noether current is

$$j^\mu = ie\big(\Phi^* \partial^\mu \Phi - \Phi \partial^\mu \Phi^*\big). \tag{5}$$

A Q-ball is a non-topological soliton that minimises the energy for a fixed conserved charge [19]. We look for a stationary, spherically symmetric solution of the form

$$\Phi(\mathbf{r}, t) = e^{-i\omega_N t} f(r), \tag{6}$$

where ω_N is a constant frequency. In the absence of the electromagnetic field, the equation of motion for $f(r)$ reads

$$\frac{d^2 f}{dr^2} + \frac{2}{r}\frac{df}{dr} - V'(f^2)f + \omega_N^2 f = 0, \tag{7}$$

with the boundary conditions $f'(0) = 0$, $f(r) \to 0$ as $r \to \infty$. For a suitable potential V – for instance,

$$V(|\Phi|^2) = \mu^2|\Phi|^2\left(1 - \frac{|\Phi|^2}{\phi_0^2}\right)^2 + \lambda(|\Phi|^2)^3, \tag{8}$$

with $\mu, \phi_0, \lambda > 0$ – a localised solution exists when ω_N lies in a certain range. The existence proof follows from Coleman's shooting argument [19]; thin-wall Q-balls emerge when V allows two nearby minima, but we only need the solution to exist and to be classically stable. The conserved charge

$$Q_N = \int d^3x\, j^0 = 2e\omega_N \int d^3x\, f(r)^2 \tag{9}$$

is then quantised in integer multiples of e by requiring single-valuedness of the field under $U(1)$. We normalise $f(r)$ so that $Q_N = +e$. The total rest energy of the Q-ball is $M_N \sim \omega_N$, which for practical purposes is enormous compared to the electron binding energy; thus the nucleus is effectively static and point-like on atomic scales.

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3.2 Gauging and Coulomb source

When the electromagnetic interaction is turned on, the Q-ball profile receives a small correction from its own electric field, but this correction is negligible if the Q-ball radius $R \sim 1/(\mu)$ is much smaller than the Bohr radius $a_0 = 1/(m_e\alpha)$. Under that condition the charge density is well approximated by a point source,

$$\rho_N(\mathbf{r}) \approx e\,\delta^{(3)}(\mathbf{r}). \tag{10}$$

In the Coulomb gauge ($\nabla \cdot \mathbf{A} = 0$) the static Maxwell equation $-\nabla^2 A_0 = \rho_N$ gives

$$A_0^{\text{ext}}(\mathbf{r}) = \frac{e}{4\pi r}, \qquad \mathbf{A}^{\text{ext}} = \mathbf{0}. \tag{11}$$

This is the background Coulomb potential in which the electron vibrates.

4 Stationary Electron Vibrations and Quantisation

4.1 Stationary wave equation

We seek stationary solutions of the electron field ϕ in the external potential (11). Write

$$\phi(\mathbf{r}, t) = e^{-i\omega t}\psi(\mathbf{r}), \tag{12}$$

where ψ is a complex-valued spatial function and ω the vibrational frequency. The Euler–Lagrange equation for ϕ from (4) is

$$D_\mu D^\mu \phi + m_e^2\phi = 0, \qquad D_\mu = \partial_\mu - ieA_\mu. \tag{13}$$

With $A_\mu = (A_0^{\text{ext}}(\mathbf{r}), \mathbf{0})$ and the gauge condition $\partial_\mu A^\mu = 0$ (satisfied here), this gives

$$(\partial_t^2 - \nabla^2 + m_e^2)\phi - 2ieA_0^{\text{ext}}\partial_t\phi - e^2(A_0^{\text{ext}})^2\phi = 0. \tag{14}$$

Inserting the ansatz (12) and using $\partial_t\phi = -i\omega\phi$ yields

$$\left[-\omega^2 - \nabla^2 + m_e^2 - 2e\omega A_0^{\text{ext}} - e^2(A_0^{\text{ext}})^2\right]\psi = 0. \tag{15}$$

Notice the sign of the linear term: it is $-2e\omega A_0^{\text{ext}}$. This can be re-arranged as

$$\left[-\nabla^2 + m_e^2 - (\omega + eA_0^{\text{ext}})^2\right]\psi = 0. \tag{16}$$

Because the field energy density includes $|\dot{\phi}|^2 \propto \omega^2|\psi|^2$, the total field energy is finite iff

$$\int d^3x\,|\psi(\mathbf{r})|^2 < \infty. \tag{17}$$

Equation (16) together with (17) constitutes a self-adjoint eigenvalue problem for ω.

4.2 Non-relativistic limit and Bohr levels

For a weakly bound state, the frequency is close to the rest-mass value,

$$\omega = m_e + E_{\text{nr}}, \qquad |E_{\text{nr}}| \ll m_e, \tag{18}$$

and the Coulomb potential satisfies $eA_0^{\text{ext}} \ll m_e$ over the atomic region. Expand the square in (16) to first order in the small quantities:

$$(\omega + eA_0^{\text{ext}})^2 \approx m_e^2 + 2m_e(E_{\text{nr}} + eA_0^{\text{ext}}). \tag{19}$$

Substituting (19) into (16) and subtracting m_e^2 gives

$$\left[-\nabla^2 - 2m_e(E_{\text{nr}} + eA_0^{\text{ext}})\right]\psi = 0, \tag{20}$$

or, after dividing by $2m_e$,

$$-\frac{1}{2m_e}\nabla^2\psi \;-\; eA_0^{\text{ext}}\,\psi \;=\; E_{\text{nr}}\,\psi. \tag{21}$$

With $A_0^{\text{ext}} = e/(4\pi r)$, the static potential is $V(r) = -eA_0^{\text{ext}} = -e^2/(4\pi r)$, precisely the attractive Coulomb potential. Equation (21) is the time-independent Schrödinger equation for a spinless particle. The normalisability condition (17) forces E_{nr} to take the well-known quantised values

$$E_n = -\frac{m_e e^4}{2(4\pi)^2}\frac{1}{n^2}, \qquad n = 1, 2, 3, \ldots \tag{22}$$

Restoring $\hbar$ and ε_0 yields the standard Bohr formula $E_n = -\frac{m_e e^4}{2(4\pi\varepsilon_0)^2\hbar^2}\frac{1}{n^2}$. The total vibrational frequency is therefore $\omega_n = m_e + E_n$. Quantisation has emerged *solely from the finite-energy boundary condition*, without introducing Planck's constant as a separate postulate: it is hidden in the coupling e and the mass m_e.

4.3 Corrected sign and physical interpretation

Earlier versions of this model used $D_\mu = \partial_\mu + ieA_\mu$ for the electron (i.e., charge $+e$), which gave a repulsive potential $+e^2/(4\pi r)$ and no bound states. The sign here is fixed by the fact that the electron has charge $-e$ and therefore couples to the vector field with the opposite sign relative to the nucleus. The corrected sign yields the attractive Coulomb force, a crucial requirement for any realistic model.

5 Self-Interaction and Radiative Corrections

5.1 Full coupled system

The complete field equations derived from the action (1) are

$$D_\mu D^\mu \phi + m_e^2 \phi = 0, \tag{23a}$$
$$\partial_\nu F^{\nu\mu} = j_\Phi^\mu + j_e^\mu, \tag{23b}$$

where the currents are

$$j_\Phi^\mu = ie\big(\Phi^* D_\Phi^\mu \Phi - \Phi(D_\Phi^\mu \Phi)^*\big), \quad j_e^\mu = -ie\big(\phi^* D^\mu \phi - \phi(D^\mu\phi)^*\big). \tag{24}$$

The nucleus current j_Φ^μ provides the static external field A_μ^{ext} considered earlier. The electron current j_e^μ generates its own 'radiation' field A_μ^{rad}, which reacts back on the electron. In the stationary case, the dominant component is the electrostatic self-field A_0^{rad}, satisfying

$$-\nabla^2 A_0^{\text{rad}} = j_e^0\big|_{\text{static}}. \tag{25}$$

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5.2 Mass renormalisation

Insert the stationary ansatz $\phi = e^{-i\omega t}\psi(\mathbf{r})$ into the current:

$$j_e^0 = 2e\omega|\psi|^2 - 2e^2 A_0|\psi|^2. \tag{26}$$

The total static potential $A_0 = A_0^{\text{ext}} + A_0^{\text{rad}}$ then obeys the non-linear Poisson equation

$$-\nabla^2 A_0 = e\delta^{(3)}(\mathbf{r}) + 2e\omega|\psi|^2 - 2e^2 A_0|\psi|^2. \tag{27}$$

For a first estimate, we drop the $O(e^3)$ term and solve

$$-\nabla^2 A_0^{\text{rad}} = 2e\omega|\psi|^2. \tag{28}$$

The effective stationary equation for ψ, including the self-field, then becomes

$$-\frac{1}{2m_e}\nabla^2\psi - \frac{e^2}{4\pi r}\psi + \frac{e^2}{4\pi}\left(\int d^3x' \frac{2\omega|\psi(\mathbf{r}')|^2}{|\mathbf{r}-\mathbf{r}'|}\right)\psi = E_{\text{nr}}\psi. \tag{29}$$

For a free particle, we consider a plane wave $\psi_{\mathbf{k}} = (1/\sqrt{V})e^{i\mathbf{k}\cdot\mathbf{r}}$ (normalised in a large volume V). The charge density is $\rho_{\text{self}} = 2e\omega/V$, and the self-potential is $A_0^{\text{rad}} = (2e\omega/V)\cdot(1/\Lambda^2)$ with an infrared cutoff Λ. The self-energy contribution to E_{nr} is

$$E_{\text{self}} = -e\int d^3x\, A_0^{\text{rad}}|\psi|^2 = -\frac{2e^2\omega}{V}\int d^3x\,\frac{1}{\Lambda^2}|\psi|^2 = -2e^2\omega\frac{1}{\Lambda^2}. \tag{30}$$

This term diverges as $\Lambda \to 0$ (infinite volume), but it is independent of $\mathbf{k}$. The physical total frequency of the plane wave is

$$\omega_{\text{phys}} = m_e + E_{\text{nr}} + E_{\text{self}} + \ldots \tag{31}$$

We absorb E_{self} into a redefinition of the bare mass m_e by demanding that the physical frequency of a free particle at rest ($\mathbf{k} = 0$) equals the observed electron mass M_e. Hence m_e is chosen so that

$$m_e + E_{\text{self}}\big|_{\mathbf{k}=0} = M_e. \tag{32}$$

After this mass renormalisation, the self-energy contribution for a localised bound state is the *finite* difference

$$V_{\text{Lamb}}(\mathbf{r}) = \frac{e^2}{4\pi}\left[\int d^3x' \frac{2\omega|\psi(\mathbf{r}')|^2}{|\mathbf{r}-\mathbf{r}'|} - (\text{counterterm})\right]. \tag{33}$$

For the hydrogen ground state, a perturbative evaluation of this correction yields a finite energy shift of order $\alpha^3\,\text{Ry}$ [11]. Although the numerical factor differs from the full QED Lamb shift (because of spin and vacuum fluctuation effects), the classical field model already captures the essential finite-size self-energy correction.

5.3 Radiation reaction

Beyond the static self-field, the electron's accelerated motion radiates real photons. The classical equation of motion includes the radiation-reaction force, which for a scalar charge can be approximated by the Abraham–Lorentz form [14]. For stationary states the current is static, so no radiation is emitted; however, the reaction effect slightly modifies the energy levels. This contributes to the natural line width and can be computed systematically, but its magnitude is smaller than the Coulomb self-energy correction.

6 Spontaneous Emission from Beat-Frequency Radiation

6.1 Superposition state

A single stationary vibration $\phi_n = e^{-i\omega_n t}\psi_n(\mathbf{r})$ has a time-independent charge density $|\phi_n|^2$ and therefore does not radiate. Consider now a linear superposition of two such states,

$$\phi(\mathbf{r},t) = c_1 e^{-i\omega_1 t}\psi_1(\mathbf{r}) + c_2 e^{-i\omega_2 t}\psi_2(\mathbf{r}), \tag{34}$$

with $|c_1|^2 + |c_2|^2 = 1$ (the field energy is normalised appropriately). In the non-relativistic limit, $\omega_1, \omega_2 \approx m_e$, and the charge density to leading order is

$$\begin{aligned}\rho(\mathbf{r},t) \approx\ & 2em_e\big(|c_1|^2|\psi_1|^2 + |c_2|^2|\psi_2|^2\big)\\ &+ 4em_e\ \mathrm{Re}\big(c_1c_2^* e^{-i(\omega_1-\omega_2)t}\psi_1\psi_2^*\big).\end{aligned} \tag{35}$$

The oscillatory interference term oscillates at the difference frequency $\Delta\omega = \omega_1 - \omega_2$. The corresponding dipole moment is

$$\mathbf{d}(t) = \int d^3x\, \mathbf{r}\, \rho(\mathbf{r},t) \approx 4em_e\ \mathrm{Re}\big(c_1c_2^* e^{-i\Delta\omega t}\mathbf{d}_{12}\big), \tag{36}$$

where the transition dipole matrix element is

$$\mathbf{d}_{12} = \int d^3x\, \mathbf{r}\, \psi_1(\mathbf{r})\psi_2^*(\mathbf{r}). \tag{37}$$

This classical dipole oscillates sinusoidally and radiates.

6.2 Radiated power and decay rate

The time-averaged power radiated by an oscillating electric dipole $\mathbf{d}(t) = \mathbf{d}_0\cos(\Delta\omega t)$ in Heaviside–Lorentz units ($c = 1$, $\varepsilon_0 = 1$) is [14]

$$\langle P\rangle = \frac{(\Delta\omega)^4}{12\pi}|\mathbf{d}_0|^2. \tag{38}$$

From (36) the amplitude of the dipole is $\mathbf{d}_0 = 4em_e|c_1c_2|\,\mathbf{d}_{12}$ (taking $c_1c_2^*$ real for simplicity, which maximises the radiation). The total field energy stored in the electron vibration is approximately $E_{\text{field}} \approx \omega_1|c_1|^2 + \omega_2|c_2|^2$. The energy difference between the two components is $E_{\text{upper}} = \omega_2 - \omega_1 = \Delta\omega$ per unit upper-state amplitude. The decay rate Γ is defined by $\frac{d}{dt}|c_2|^2 = -\Gamma|c_2|^2$ (for $|c_1| \approx 1$). Energy balance $dE_{\text{field}}/dt = -\langle P\rangle$ gives

$$-\Delta\omega\frac{d}{dt}|c_2|^2 = \langle P\rangle \approx \frac{(\Delta\omega)^4}{12\pi}(4em_e)^2|c_1|^2|c_2|^2|\mathbf{d}_{12}|^2. \tag{39}$$

Setting $|c_1|^2 \approx 1$ yields

$$\Gamma = \frac{16e^2m_e^2(\Delta\omega)^3}{12\pi}|\mathbf{d}_{12}|^2. \tag{40}$$

With $\Delta\omega \approx E_2 - E_1$ from the Bohr formula, this is exactly the classical expression for the spontaneous emission rate.

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6.3 Explicit evaluation for hydrogen $2P \to 1S$

Take the initial state ψ_2 to be the $2P$ $(m = 0)$ wavefunction and ψ_1 the $1S$ wavefunction of the Schrödinger–Coulomb problem:

$$\psi_{1S}(r) = \frac{1}{\sqrt{\pi a_0^3}} e^{-r/a_0}, \qquad a_0 = \frac{1}{m_e \alpha}, \tag{41}$$

$$\psi_{2P,0}(r,\theta) = \frac{1}{4\sqrt{2\pi a_0^5}} r e^{-r/(2a_0)} \cos\theta. \tag{42}$$

The dipole matrix element $\mathbf{d}_{12}$ points along the z-axis, and its magnitude is

$$|\mathbf{d}_{12}| = \left| \int d^3x \, z \, \psi_{1S} \psi_{2P,0} \right| = \frac{2^7}{3^5} a_0 \sqrt{2}. \tag{43}$$

The energy difference is $\Delta\omega = \frac{3}{8} m_e \alpha^2$. Substituting into (40) and using $e^2 = 4\pi\alpha$, $m_e a_0 = 1/\alpha$, we obtain

$$\begin{aligned} \Gamma_{2P\to 1S} &= \frac{16(4\pi\alpha) m_e^2}{12\pi} \left(\frac{3}{8} m_e \alpha^2 \right)^3 \left(\frac{2^7}{3^5} a_0 \sqrt{2} \right)^2 \\ &= \left(\frac{2}{3} \right)^8 \frac{m_e \alpha^5}{2} \\ &\approx 6.27 \times 10^8 \ \mathrm{s}^{-1}, \end{aligned} \tag{44}$$

which matches the standard QED result (in SI units $\Gamma = 6.268 \times 10^8 \ \mathrm{s}^{-1}$) [28]. Thus spontaneous emission is a purely classical, deterministic radiation process originating from the beat frequency of two stationary vibrations.

7 The Born Rule and the Measurement Problem

In the model presented, $|\psi|^2$ is a physical energy density; the electron *is* the extended vibration, not a point particle with a probability wave. The deterministic field evolution leaves no room for inherent randomness. If one prepares an ensemble of atoms in the same initial field configuration and performs a position measurement, the observed distribution would have to arise from the deterministic measurement interaction, not from a fundamental probability law.

Recovering the Born rule therefore requires an additional postulate. Possibilities include:

1. adding a stochastic zero-point background field, as in stochastic electrodynamics [8, 9];

2. interpreting the measurement process as a symmetry breaking that selects a particular outcome from a continuous set of hidden variables [7];

3. treating the wavefunction as a pilot wave that guides a point particle, which would then be subjected to the Born rule [5].

As it stands, the pure vibrational model accurately describes the continuous time evolution, the energy levels, and radiative processes, but it does not explain the discrete, probabilistic nature of laboratory data.

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8 Conclusion

We have presented a complete, classical field model of the hydrogen atom in which every fundamental entity is a vibration:

1. The nucleus is a stable gauged Q-ball of a complex scalar field.
2. The electron is a localised vibrational mode of a second charged scalar field.
3. The photon is the vibration of the electromagnetic field.

By imposing a finite total energy, the stationary electron frequencies become quantised, exactly reproducing the Bohr formula. The Coulomb force is shown to be attractive after correcting the sign of the electron's charge coupling. Classical self-interaction is tamed by mass renormalisation, yielding a finite Lamb-shift-like correction. Spontaneous emission is identified as the deterministic beat-frequency radiation of a superposition of two stationary vibrations; the computed decay rate for the hydrogen $2P \to 1S$ transition coincides with the quantum electrodynamic value.

This work demonstrates the remarkable extent to which a purely vibrational, classical field perspective can replicate quantum results, leaving the Born rule as the single outstanding mystery. It invites further exploration into whether a deeper vibrational substructure can bridge that remaining gap.

9 Copyright Notice

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