Calculating electromagnetic properties of the quantum vacuum using electrodynamics to describe the interaction of a photon with vacuum fluctuations

G. Bruce Mainland and Bernard Mulligan, Department of Physics

The International Association for Relativistic Dynamics
14^{th} Biennial Conference
Aalto University, Espoo, Finland
3-6 June 2024

FIRST EXPERIMENTAL CALCULATION OF THE SPEED OF LIGHT IN THE VACUUM: 1676

- Jupiter's moon Io has an orbital period of 1.77 Earth days.

FIRST EXPERIMENTAL CALCULATION OF THE SPEED OF LIGHT IN THE VACUUM: 1676

- Jupiter's moon Io has an orbital period of 1.77 Earth days.
- As seen from Earth, Io is eclipsed by Jupiter once each orbit.

FIRST EXPERIMENTAL CALCULATION OF THE SPEED OF LIGHT IN THE VACUUM: 1676

- Jupiter's moon Io has an orbital period of 1.77 Earth days.
- As seen from Earth, Io is eclipsed by Jupiter once each orbit.

	Diameter of Earth's orbit about the sun	Time for light to travel the diameter	speed of light in the vacuum
Roemer	2.8×10^{11}m	22 min	2.1×10^{8} m/s

FIRST EXPERIMENTAL CALCULATION OF THE SPEED OF LIGHT IN THE VACUUM: 1676

- Jupiter's moon Io has an orbital period of 1.77 Earth days.
- As seen from Earth, Io is eclipsed by Jupiter once each orbit.

	Diameter of Earth's orbit about sun	Time for light to travel the diameter	speed of light in the vacuum
Roemer	2.8×10^{11}m	22 min	2.1×10^{8} m/s
Today	2.99×10^{11}m	16.7 min	3.00×10^{8} m/s

INTRODUCTION

- A fundamental postulate of physics is that the structure of a physical system determines the properties of the system.

INTRODUCTION

- A fundamental postulate of physics is that the structure of a physical system determines the properties of the system.
- To calculate the speed c of light in the vacuum, the physical system is a photon traveling through the quantum vacuum.

INTRODUCTION

- A fundamental postulate of physics is that the structure of a physical system determines the properties of the system.
- To calculate the speed c of light in the vacuum, the physical system is a photon traveling through the quantum vacuum.
- The speed c of light in the vacuum is an electromagnetic property of the quantum vacuum. Thus it is possible to calculate c using Maxwell's equations, quantum electrodynamics, and quantum mechanics to describe the interaction of a photon with the quantum vacuum.

THE QUANTUM VACUUM

- A perfect vacuum contains no ordinary matter.

THE QUANTUM VACUUM

- A perfect vacuum contains no ordinary matter.
- Field theory reveals that the quantum vacuum is manifest as transient, particle-antiparticle pairs that appear in – and disappear from – the quantum vacuum. These transient, particle-antiparticle pairs are called type 1 vacuum fluctuations.

THE QUANTUM VACUUM

- A perfect vacuum contains no ordinary matter.
- Field theory reveals that the quantum vacuum is manifest as transient, particle-antiparticle pairs that appear in – and disappear from – the quantum vacuum. These transient, particle-antiparticle pairs are called type 1 vacuum fluctuations.
- Vacuum energy is the energy source for the creation of type 1 vacuum fluctuations.

TYPE 1 VACUUM FLUCTUATIONS

- are on shell: $(mc^2)^2 = E^2 - (\mathbf{P}c)^2$

TYPE 1 VACUUM FLUCTUATIONS

- are on shell: $(mc^2)^2 = E^2 - (\mathbf{P}c)^2$
- violate conservation of ordinary energy and exist for a transient time Δt permitted by the Heisenberg uncertainty principle.

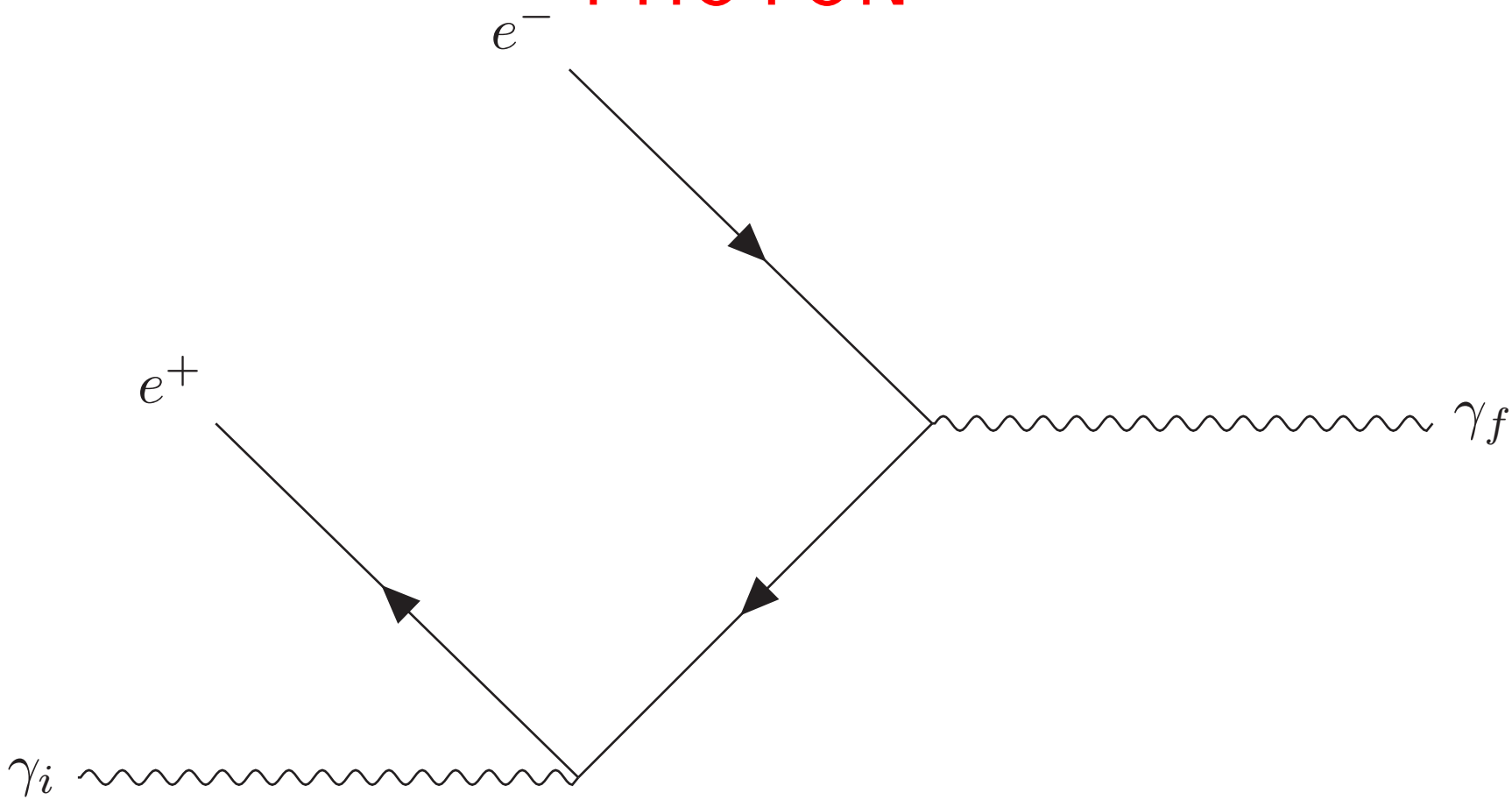
TYPE 1 VACUUM FLUCTUATIONS

- are on shell: $(mc^2)^2 = E^2 - (\mathbf{P}c)^2$
- violate conservation of ordinary energy and exist for a transient time Δt permitted by the Heisenberg uncertainty principle.
- when created conserve electric charge, lepton number, baryon number, and angular momentum.

TYPE 1 VACUUM FLUCTUATIONS

- are on shell: $(mc^2)^2 = E^2 - (\mathbf{P}c)^2$
- violate conservation of ordinary energy and exist for a transient time Δt permitted by the Heisenberg uncertainty principle.
- when created conserve electric charge, lepton number, baryon number, and angular momentum.
- appear as external particles in Feynman diagrams.

FEYNMAN DIAGRAM OF A TYPE 1 ELECTRON-POSITRON VACUUM FLUCTUATION INTERACTING WITH A PHOTON



TYPE 1 VACUUM FLUCTUATIONS

- cannot exert a force on ordinary matter.

TYPE 1 VACUUM FLUCTUATIONS

- cannot exert a force on ordinary matter.
- If they could exert a force, they could do work on ordinary particles. Then when a vacuum fluctuation vanished, the energy associated with any work done by the vacuum fluctuation would remain, permanently violating conservation of ordinary energy.

TYPE 2 VACUUM FLUCTUATIONS

- do not contribute to processes involving ordinary matter.

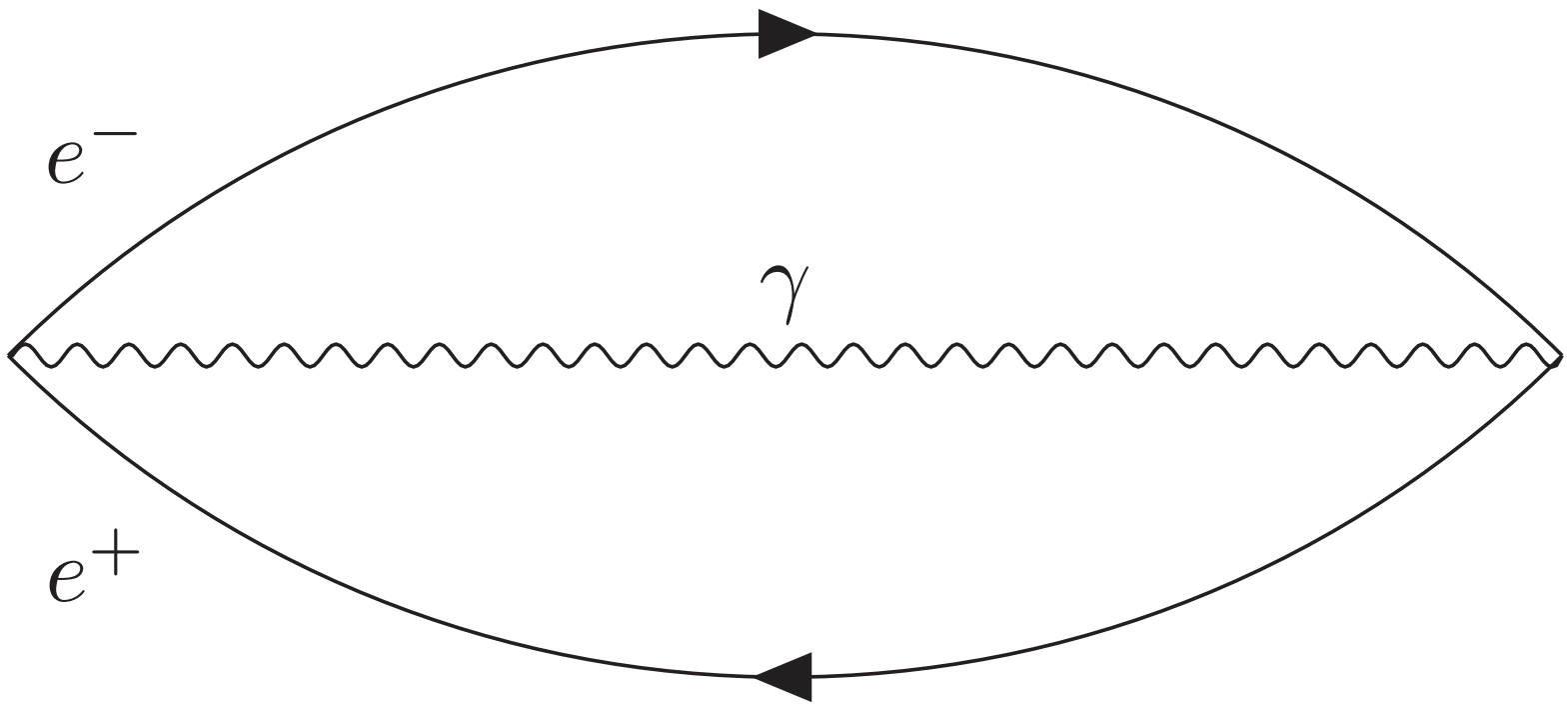
TYPE 2 VACUUM FLUCTUATIONS

- do not contribute to processes involving ordinary matter.
- are sometimes called vacuum diagrams or vacuum bubbles, a class of disconnected Feynman diagrams for which virtual particles appear in and then vanish from the vacuum.

TYPE 2 VACUUM FLUCTUATIONS

- do not contribute to processes involving ordinary matter.
- are sometimes called vacuum diagrams or vacuum bubbles, a class of disconnected Feynman diagrams for which virtual particles appear in and then vanish from the vacuum.
- are off shell: $(mc^2)^2 \neq E^2 - (\mathbf{P}c)^2$

FEYNMAN DIAGRAM FOR A TYPE 2 VACUUM FLUCTUATION: (VACUUM DIAGRAM OR VACUUM BUBBLE)



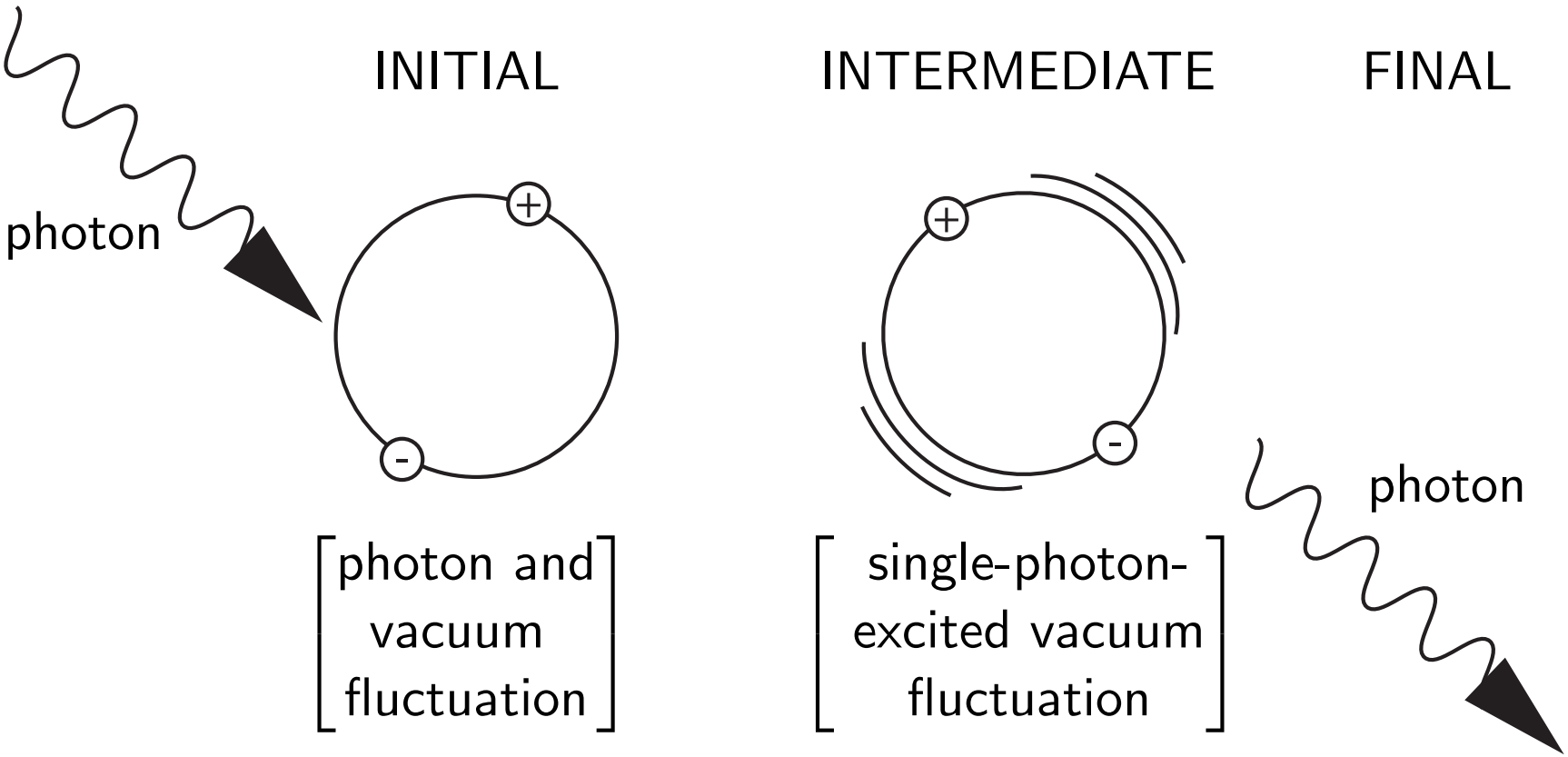
THE SPEED OF LIGHT IN THE QUANTUM VACUUM

- While present, type 1 vacuum fluctuations slow the progress of photons, similarly to the way that an ordinary dielectric slows photons.

THE SPEED OF LIGHT IN THE QUANTUM VACUUM

- While present, type 1 vacuum fluctuations slow the progress of photons, similarly to the way that an ordinary dielectric slows photons.
- The slowing of photons by vacuum fluctuations determines the permittivity of the vacuum, the speed of light in the vacuum, and the fine-structure constant.

PHOTON POLARIZING A VACUUM FLUCTUATION



EARLY LITERATURE DISCUSSING VACUUM FLUCTUATIONS

- Furry & Oppenheimer (1934): "Because of the polarizability of the nascent pairs [type 1 vacuum fluctuations], the dielectric constant of space into which no matter has been introduced differs from that of truly empty space."

EARLY LITERATURE DISCUSSING VACUUM FLUCTUATIONS

- Furry & Oppenheimer (1934): "Because of the polarizability of the nascent pairs [type 1 vacuum fluctuations], the dielectric constant of space into which no matter has been introduced differs from that of truly empty space."
- Pauli & Weisskopf (1934) discussed the idea that the vacuum could be treated as a medium with electric and magnetic polarizability.

RESULTS:
THEORETICAL FORMULA FOR ϵ_0

$$\epsilon_{0\,\text{theory}} = \frac{6\mu_0}{\pi}\left(\frac{8e^2}{\hbar}\right)^2 = 9.10 \times 10^{-12}\frac{\text{C}^2}{\text{Nm}^2}$$

RESULTS: THEORETICAL FORMULA FOR ϵ_0

$$\epsilon_{0\ \text{theory}} = \frac{6\mu_0}{\pi}\left(\frac{8e^2}{\hbar}\right)^2 = 9.10 \times 10^{-12}\frac{\text{C}^2}{\text{Nm}^2}$$

$$\epsilon_{0\ \text{accepted}} = 8.85 \times 10^{-12}\frac{\text{C}^2}{\text{Nm}^2}$$

RESULTS: THEORETICAL FORMULA FOR ϵ_0

$$\epsilon_{0\ \text{theory}} = \frac{6\mu_0}{\pi}\left(\frac{8e^2}{\hbar}\right)^2 = 9.10 \times 10^{-12}\frac{\text{C}^2}{\text{Nm}^2}$$

$$\epsilon_{0\ \text{accepted}} = 8.85 \times 10^{-12}\frac{\text{C}^2}{\text{Nm}^2}$$

$\epsilon_{0\ \text{theory}}$ is 2.8 % larger than the accepted value.

THEORETICAL FORMULA FOR THE SPEED c OF LIGHT IN THE VACUUM

Using $c = 1/\sqrt{\mu_0 \epsilon_0}$ and the formula for $\epsilon_{0\,\mathrm{theory}}$

THEORETICAL FORMULA FOR THE SPEED c OF LIGHT IN THE VACUUM

Using $c = 1/\sqrt{\mu_0 \epsilon_0}$ and the formula for $\epsilon_{0\,\mathrm{theory}}$

$$c_{\,\mathrm{theory}} = \sqrt{\frac{\pi}{6}\frac{\hbar}{8e^2\mu_0}} = 2.96 \times 10^8 \mathrm{m/s}$$

THEORETICAL FORMULA FOR THE SPEED c OF LIGHT IN THE VACUUM

Using $c = 1/\sqrt{\mu_0 \epsilon_0}$ and the formula for $\epsilon_{0\,\mathrm{theory}}$

$$c_{\,\mathrm{theory}} = \sqrt{\frac{\pi}{6}} \frac{\hbar}{8e^2\mu_0} = 2.96 \times 10^8 \mathrm{m/s}$$

$$c_{\,\mathrm{defined}} = 2.998 \times 10^8 \mathrm{m/s}$$

THEORETICAL FORMULA FOR THE SPEED c OF LIGHT IN THE VACUUM

Using $c = 1/\sqrt{\mu_0 \epsilon_0}$ and the formula for $\epsilon_{0\,\mathrm{theory}}$

$$c_{\,\mathrm{theory}} = \sqrt{\frac{\pi}{6}\frac{\hbar}{8e^2\mu_0}} = 2.96 \times 10^8 \mathrm{m/s}$$

$$c_{\,\mathrm{defined}} = 2.998 \times 10^8 \mathrm{m/s}$$

$c_{\,\mathrm{theory}}$ is 1.3 % less than the defined value.

POSTULATES OF SPECIAL RELATIVITY

1. Relativity Postulate: The laws of physics are the same for observers in all inertial reference frames.

POSTULATES OF SPECIAL RELATIVITY

1. Relativity Postulate: The laws of physics are the same for observers in all inertial reference frames.

2. Speed-of-Light Postulate: The speed of light in the vacuum has the same value c in any direction in all inertial reference frames.

THE CALCULATED VALUE OF c MUST SATISFY THE SPEED-OF-LIGHT POSTULATE

THE CALCULATED VALUE OF C MUST SATISFY THE SPEED-OF-LIGHT POSTULATE

- The quantum vacuum is isotropic and at rest with respect to every inertial frame so the quantum vacuum is isotropic and the same in every inertial frame.

THE CALCULATED VALUE OF C MUST SATISFY THE SPEED-OF-LIGHT POSTULATE

- The quantum vacuum is isotropic and at rest with respect to every inertial frame so the quantum vacuum is isotropic and the same in every inertial frame.
- Maxwell's equations, quantum electrodynamics (QED), and quantum mechanics are the same in every inertial frame. (Relativity Postulate)

THE CALCULATED VALUE OF c MUST SATISFY THE SPEED-OF-LIGHT POSTULATE

- The quantum vacuum is isotropic and at rest with respect to every inertial frame so the quantum vacuum is isotropic and the same in every inertial frame.
- Maxwell's equations, quantum electrodynamics (QED), and quantum mechanics are the same in every inertial frame. (Relativity Postulate)
- c is calculated from properties of the quantum vacuum, Maxwell's equations, QED, and quantum mechanics so the calculated value of c is automatically the same in all directions in every inertial reference frame.

CALCULATION OF THE FINE-STRUCTURE CONSTANT

The fine-structure constant

$$\alpha \equiv \frac{e^2}{4\pi\epsilon_0\hbar c}\,.$$

CALCULATION OF THE FINE-STRUCTURE CONSTANT

The fine-structure constant

$$\alpha \equiv \frac{e^2}{4\pi\epsilon_0\hbar c}\,.$$

Substituting the formulas for $\epsilon_{0\ \mathrm{theory}}$ and $c_{\,\mathrm{theory}}$ into the above expression for α,

$$\left(\frac{1}{\alpha}\right)_{\mathrm{theory}} = 8^2\sqrt{3\pi/2} = 138.9\ldots\,,$$

$$\left(\frac{1}{\alpha}\right)_{\mathrm{experimental}} = 137.0\ldots\quad.$$

CALCULATION OF THE FINE-STRUCTURE CONSTANT

The fine-structure constant

$$\alpha \equiv \frac{e^2}{4\pi\epsilon_0\hbar c}\,.$$

Substituting the formulas for $\epsilon_{0\ \mathrm{theory}}$ and $c_{\,\mathrm{theory}}$ into the above expression for α,

$$\left(\frac{1}{\alpha}\right)_{\mathrm{theory}} = 8^2\sqrt{3\pi/2} = 138.9\ldots\,,$$

$$\left(\frac{1}{\alpha}\right)_{\mathrm{experimental}} = 137.0\ldots\quad.$$

$\left(\frac{1}{\alpha}\right)_{\mathrm{theory}}$ is 1.4 % larger than $\left(\frac{1}{\alpha}\right)_{\mathrm{experimental}}$

PERMITTIVITY ϵ OF A DIELECTRIC

The permittivity ϵ of a dielectric satisfies the following equation:

$$\text{Dielectric: } \epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \Sigma_i N_i \langle \mathbf{p}_i \rangle,$$

PERMITTIVITY ϵ OF A DIELECTRIC

The permittivity ϵ of a dielectric satisfies the following equation:

$$\text{Dielectric: } \epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \Sigma_i N_i \langle \mathbf{p}_i \rangle,$$

- $\mathbf{E}$= external electric field

PERMITTIVITY ϵ OF A DIELECTRIC

The permittivity ϵ of a dielectric satisfies the following equation:

$$\text{Dielectric: } \epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \Sigma_i N_i \langle \mathbf{p}_i \rangle,$$

- $\mathbf{E}$= external electric field
- N_i = number of the i^{th} type of polarized atoms or molecules per unit volume,

PERMITTIVITY ϵ OF A DIELECTRIC

The permittivity ϵ of a dielectric satisfies the following equation:

$$\text{Dielectric: } \epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \Sigma_i N_i \langle \mathbf{p}_i \rangle,$$

- $\mathbf{E}$= external electric field
- N_i = number of the i^{th} type of polarized atoms or molecules per unit volume,
- $\langle \mathbf{p}_i \rangle$ = expectation value of an electric dipole moment of the i^{th} type of polarized atom or molecule.

PERMITTIVITY ϵ_0 OF THE VACUUM

Dielectric: $\epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \Sigma_i N_i \langle \mathbf{p}_i \rangle$,

The following changes must be made to the above formula if it is to describe the vacuum instead of a dielectric:

PERMITTIVITY ϵ_0 OF THE VACUUM

Dielectric: $\epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \Sigma_i N_i \langle \mathbf{p}_i \rangle$,

The following changes must be made to the above formula if it is to describe the vacuum instead of a dielectric:

- The vacuum is the dielectric: there is no background permittivity. $\epsilon_0 \mathbf{E} \to 0$.

PERMITTIVITY ϵ_0 OF THE VACUUM

Dielectric: $\epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \Sigma_i N_i \langle \mathbf{p}_i \rangle$,

The following changes must be made to the above formula if it is to describe the vacuum instead of a dielectric:

- The vacuum is the dielectric: there is no background permittivity. $\epsilon_0 \mathbf{E} \to 0$.
- The vacuum is the dielectric: $\epsilon \mathbf{E} \to \epsilon_0 \mathbf{E}$

PERMITTIVITY ϵ_0 OF THE VACUUM

Dielectric: $\epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \Sigma_i N_i \langle \mathbf{p}_i \rangle$,

The following changes must be made to the above formula if it is to describe the vacuum instead of a dielectric:

- The vacuum is the dielectric: there is no background permittivity. $\epsilon_0 \mathbf{E} \to 0$.
- The vacuum is the dielectric: $\epsilon \mathbf{E} \to \epsilon_0 \mathbf{E}$
- $N_i \to N_i^{\gamma+\mathrm{VF}}$

PERMITTIVITY ϵ_0 OF THE VACUUM

Dielectric: $\epsilon\mathbf{E} = \epsilon_0\mathbf{E} + \Sigma_i N_i \langle \mathbf{p}_i \rangle$,

The following changes must be made to the above formula if it is to describe the vacuum instead of a dielectric:

- The vacuum is the dielectric: there is no background permittivity. $\epsilon_0\mathbf{E} \to 0$.
- The vacuum is the dielectric: $\epsilon\mathbf{E} \to \epsilon_0\mathbf{E}$
- $N_i \to N_i^{\gamma+\mathrm{VF}}$
- $\langle \mathbf{p}_i \rangle \to \langle \mathbf{p}_i^{\gamma+\mathrm{VF}} \rangle = K_i^{\gamma+\mathrm{VF}}\mathbf{E}$, where $K_i^{\gamma+\mathrm{VF}}$ is a constant.

PERMITTIVITY ϵ_0 OF THE VACUUM

Dielectric: $\epsilon \mathbf{E} = \epsilon_0 \mathbf{E} + \sum_i N_i \langle \mathbf{p}_i \rangle$,

The following changes must be made to the above formula if it is to describe the vacuum instead of a dielectric:

- The vacuum is the dielectric: there is no background permittivity. $\epsilon_0 \mathbf{E} \to 0$.
- The vacuum is the dielectric: $\epsilon \mathbf{E} \to \epsilon_0 \mathbf{E}$
- $N_i \to N_i^{\gamma+\mathrm{VF}}$
- $\langle \mathbf{p}_i \rangle \to \langle \mathbf{p}_i^{\gamma+\mathrm{VF}} \rangle = K_i^{\gamma+\mathrm{VF}} \mathbf{E}$, where $K_i^{\gamma+\mathrm{VF}}$ is a constant.

Vacuum: $\epsilon_0 \mathbf{E} = \sum_i N_i^{\gamma+\mathrm{VF}} K_i^{\gamma+\mathrm{VF}} \mathbf{E}$

PERMITTIVITY ϵ_0 OF THE VACUUM

$$\text{Dielectric: } \epsilon\mathbf{E} = \epsilon_0\mathbf{E} + \Sigma_i N_i \langle \mathbf{p}_i \rangle,$$

The following changes must be made to the above formula if it is to describe the vacuum instead of a dielectric:

- The vacuum is the dielectric: there is no background permittivity. $\epsilon_0\mathbf{E} \to 0$.
- The vacuum is the dielectric: $\epsilon\mathbf{E} \to \epsilon_0\mathbf{E}$
- $N_i \to N_i^{\gamma+\mathrm{VF}}$
- $\langle \mathbf{p}_i \rangle \to \langle \mathbf{p}_i^{\gamma+\mathrm{VF}} \rangle = K_i^{\gamma+\mathrm{VF}}\mathbf{E}$, where $K_i^{\gamma+\mathrm{VF}}$ is a constant.

$$\text{Vacuum: } \epsilon_0\mathbf{E} = \sum_i N_i^{\gamma+\mathrm{VF}} K_i^{\gamma+\mathrm{VF}}\mathbf{E}$$

$$\text{Vacuum: } \epsilon_0 = \sum_i N_i^{\gamma+\mathrm{VF}} K_i^{\gamma+\mathrm{VF}}$$

WHY DON'T QUARK-ANTIQUARK TYPE 1 VACUUM FLUCTUATIONS CONTRIBUTE SIGNIFICANTLY TO ϵ_0?

$$\epsilon_0 = \sum_i N_i^{\gamma+\mathrm{VF}} K_i^{\gamma+\mathrm{VF}}$$

WHY DON'T QUARK-ANTIQUARK TYPE 1 VACUUM FLUCTUATIONS CONTRIBUTE SIGNIFICANTLY TO ϵ_0?

$$\epsilon_0 = \sum_i N_i^{\gamma+\mathrm{VF}} K_i^{\gamma+\mathrm{VF}}$$

Electron-positron vacuum fluctuations appear in the vacuum as parapositronium, the most tightly bound state that has zero angular momentum,

$$N_{\mathrm{p-Ps}}^{\gamma+\mathrm{VF}} K_{\mathrm{p-Ps}}^{\gamma+\mathrm{VF}} \sim \left(\frac{m_e c^2}{E_{\mathrm{p-Ps\ Binding}}} \right)^2$$

WHY DON'T QUARK-ANTIQUARK TYPE 1 VACUUM FLUCTUATIONS CONTRIBUTE SIGNIFICANTLY TO ϵ_0?

$$\epsilon_0 = \sum_i N_i^{\gamma+\mathrm{VF}} K_i^{\gamma+\mathrm{VF}}$$

Electron-positron vacuum fluctuations appear in the vacuum as parapositronium, the most tightly bound state that has zero angular momentum,

$$N_{\mathrm{p-Ps}}^{\gamma+\mathrm{VF}} K_{\mathrm{p-Ps}}^{\gamma+\mathrm{VF}} \sim \left(\frac{m_e c^2}{E_{\mathrm{p-Ps\ Binding}}} \right)^2$$

$$\sim \left(\frac{0.511 Mev}{6.8 eV} \right)^2$$

WHY DON'T QUARK-ANTIQUARK TYPE 1 VACUUM FLUCTUATIONS CONTRIBUTE SIGNIFICANTLY TO ϵ_0?

$$\epsilon_0 = \sum_i N_i^{\gamma+\mathrm{VF}} K_i^{\gamma+\mathrm{VF}}$$

Electron-positron vacuum fluctuations appear in the vacuum as parapositronium, the most tightly bound state that has zero angular momentum,

$$N_{\mathrm{p-Ps}}^{\gamma+\mathrm{VF}} K_{\mathrm{p-Ps}}^{\gamma+\mathrm{VF}} \sim \left(\frac{m_e c^2}{E_{\mathrm{p-Ps\ Binding}}} \right)^2$$

$$\sim \left(\frac{0.511 Mev}{6.8 eV} \right)^2$$

$$\sim 5.6 \times 10^9$$

WHY DON'T QUARK-ANTIQUARK TYPE 1 VACUUM FLUCTUATIONS CONTRIBUTE SIGNIFICANTLY TO ϵ_0?

$$\epsilon_0 = \sum_i N_i^{\gamma+\mathrm{VF}} K_i^{\gamma+\mathrm{VF}}$$

Electron-positron vacuum fluctuations appear in the vacuum as parapositronium, the most tightly bound state that has zero angular momentum,

$$N_{\mathrm{p-Ps}}^{\gamma+\mathrm{VF}} K_{\mathrm{p-Ps}}^{\gamma+\mathrm{VF}} \sim \left(\frac{m_e c^2}{E_{\mathrm{p-Ps\ Binding}}} \right)^2$$

$$\sim \left(\frac{0.511 Mev}{6.8 eV} \right)^2$$

$$\sim 5.6 \times 10^9$$

Charged-lepton-antilepton vacuum fluctuations contribute much more to the permittivity of the vacuum than quark-antiquark vacuum fluctuations.

NUMBER DENSITY OF CHARGED LEPTON-ANTILEPTON VACUUM FLUCTUATIONS

- Number density $_{e-\bar{e}\,\mathrm{VF}} = 1.1 \times 10^{39}/\mathrm{m}^3$

NUMBER DENSITY OF CHARGED LEPTON-ANTILEPTON VACUUM FLUCTUATIONS

- Number density $_{e-\bar{e}\,\mathrm{VF}} = 1.1 \times 10^{39}/\mathrm{m}^3$
- Number density $_{\mu-\bar{\mu}\,\mathrm{VF}} = 9.8 \times 10^{45}/\mathrm{m}^3$

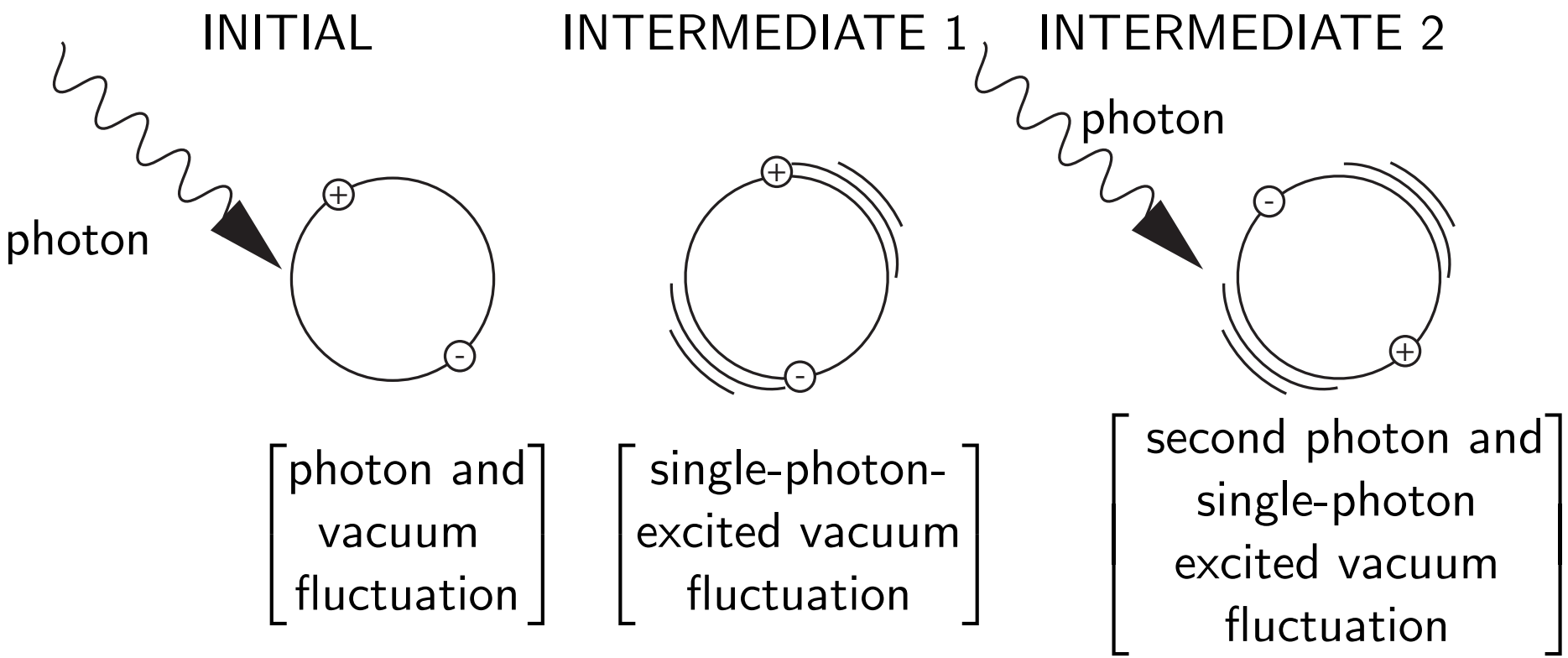
NUMBER DENSITY OF CHARGED LEPTON-ANTILEPTON VACUUM FLUCTUATIONS

- Number density $_{e-\bar{e}\,\mathrm{VF}} = 1.1 \times 10^{39}/\mathrm{m}^3$
- Number density $_{\mu-\bar{\mu}\,\mathrm{VF}} = 9.8 \times 10^{45}/\mathrm{m}^3$
- Number density $_{\tau-\bar{\tau}\,\mathrm{VF}} = 4.7 \times 10^{49}/\mathrm{m}^3$

NUMBER DENSITY OF CHARGED LEPTON-ANTILEPTON VACUUM FLUCTUATIONS

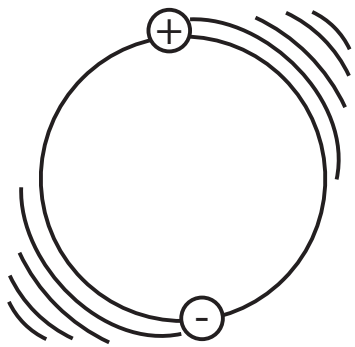
- Number density $_{e-\bar{e}\,\mathrm{VF}} = 1.1 \times 10^{39}/\mathrm{m}^3$
- Number density $_{\mu-\bar{\mu}\,\mathrm{VF}} = 9.8 \times 10^{45}/\mathrm{m}^3$
- Number density $_{\tau-\bar{\tau}\,\mathrm{VF}} = 4.7 \times 10^{49}/\mathrm{m}^3$
- For comparison, the number density of atoms or molecules in an ideal gas at STP$=$ $2.7 \times 10^{25}/\mathrm{m}^3$

TWO PHOTONS POLARIZING A VACUUM FLUCTUATION

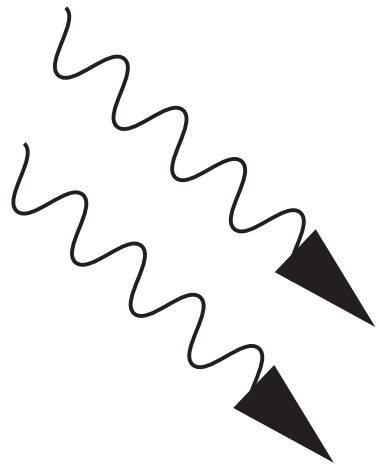


TWO PHOTONS POLARIZING A VACUUM FLUCTUATION - CONTINUED

INTERMEDIATE 3



FINAL



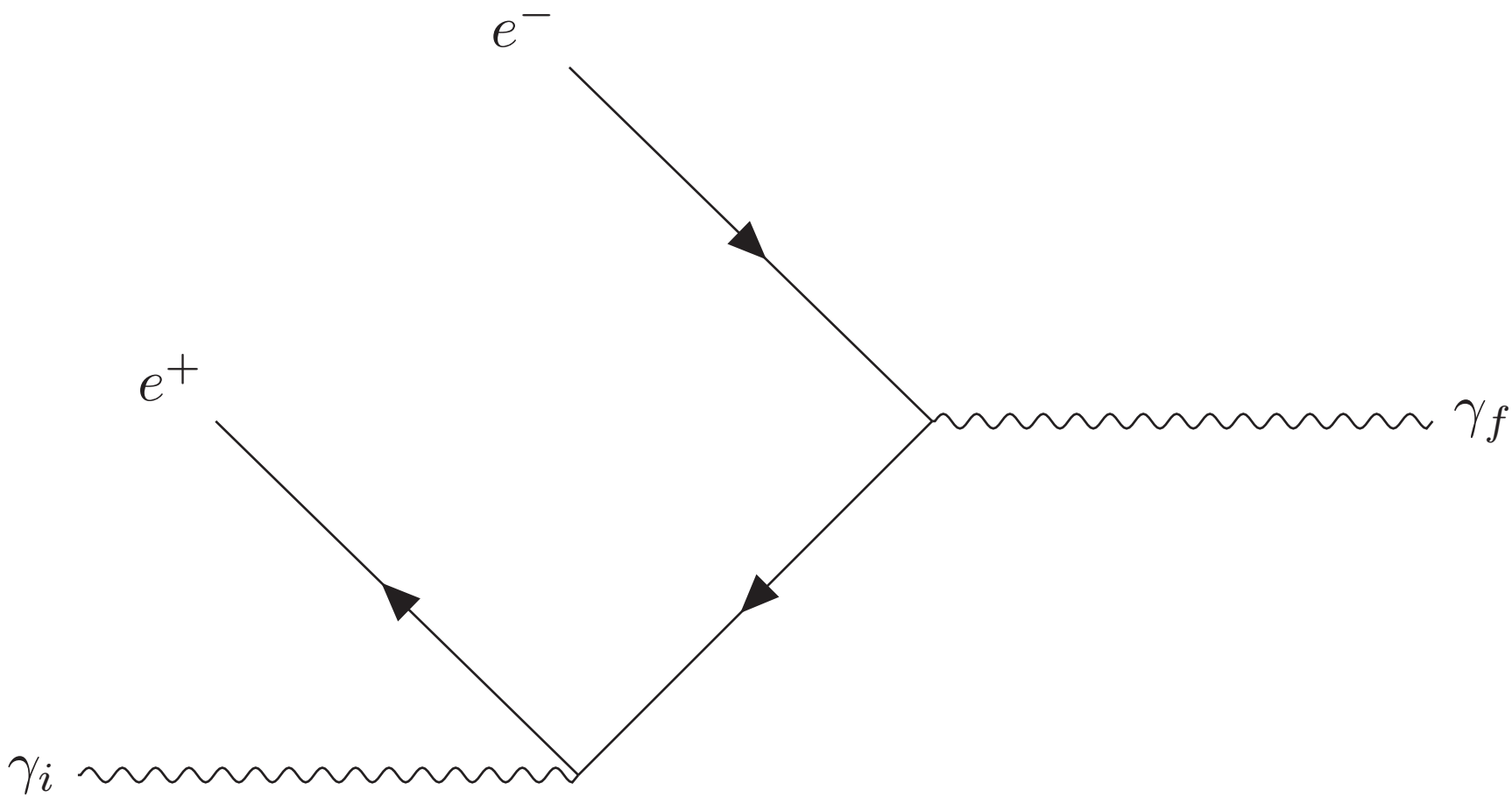
[two-photon-excited vacuum fluctuation]

[2 photons]

WHY OUR RESULTS MAY BE CORRECT

- The values for ϵ_0, c, and α are correct to within a few percent.

FEYNMAN DIAGRAM OF A PHOTON-EXCITED PARAPOSITRONIUM VACUUM FLUCTUATION DECAYING INTO A PHOTON



WHY OUR RESULTS MAY BE CORRECT

- The values for ϵ_0, c, and α are all correct to within a few percent.
- The calculated value of c automatically satisfies the second postulate of special relativity, eliminating the need for the postulate.

WHY OUR RESULTS MAY BE CORRECT

- The values for ϵ_0, c, and α are all correct to within a few percent.
- The calculated value of c automatically satisfies the second postulate of special relativity, eliminating the need for the postulate.
- The electromagnetic properties of the quantum vacuum are calculated using standard physics (Maxwell's equations, quantum electrodynamics, and quantum mechanics) to describe the interaction of a photon with the quantum vacuum. The only new physics is interaction of photons with the quantum vacuum.

RESPONSE FROM THE PHYSICS COMMUNITY

- An article published in March, 2020, has been viewed online by more than 6,100 different individuals.

RESPONSE FROM THE PHYSICS COMMUNITY

- An article published in March, 2020, has been viewed online by more than 6,100 different individuals.
- A second article published in February, 2022, has been viewed online by more than 1,500 different individuals.

RESPONSE FROM THE PHYSICS COMMUNITY

- An article published in March, 2020, has been viewed online by more than 6,100 different individuals.
- A second article published in February, 2022, has been viewed online by more than 1,500 different individuals.
- Fewer than 10 people have contacted us: to date no one has pointed out an error.

ONGOING RESEARCH

- Calculation of electromagnetic properties of the vacuum to next order in the fine-structure constant α.

ONGOING RESEARCH

- Calculation of electromagnetic properties of the vacuum to next order in the fine-structure constant α.
- Calculation of the effect of a vacuum fluctuation interacting with two photons.

ONGOING RESEARCH

- Calculation of electromagnetic properties of the vacuum to next order in the fine-structure constant α.
- Calculation of the effect of a vacuum fluctuation interacting with two photons.
- Calculation of the gravitational constant G, a gravitational property of the quantum vacuum.