Space-like Motion of Massless Particles

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by

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Organization of the Talk

- 1. Classical motion of a time-like particle
- 2. Classical space-like motion
- 3. Semi-classical Photon Wave function from atomic decay
- 4. Classical Retarded and the quantum Feynman Propagator
- 5. Time and space-like photons in Bhabha scattering
- 6. Why the S-matrix
- 7. Feynman diagram analysis of Opera
- 8. Conclusions and open problems

Classical Time-like Motion

$$x^\mu(\tau) = (\frac{P^\mu}{mc})(c\tau); \quad P^2 = P^\mu P_\mu = (mc)^2$$

$$\eta^{oo} = +1$$

$$x^2 = x^\mu x_\mu = (c\tau)^2$$

$$P^\mu = \quad mU^\mu \; ; \; U^\mu U_\mu = c^2 \; ; \; U^\mu = c\gamma(1, \beta)$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \; ; \; \beta = \frac{\mathbf{v}}{c},$$

$$\frac{\tau}{r} = \frac{m}{|\mathbf{P}|}$$

Classical Space-like

$$x^\mu(L) = \qquad (\frac{Q^\mu}{\mu c})L; \quad Q^2 = Q^\mu Q_\mu = -(\mu c)^2$$

$$x^2 = x^\mu x_\mu = -L^2,$$

$$Q^\mu = \mu V^\mu \; ; \; V^\mu V_\mu = -c^2 \; ; \; V^\mu = c\tilde{\gamma}(1, \tilde{\beta})$$

$$\tilde{\gamma} = \frac{1}{\sqrt{\tilde{\beta}^2 - 1}}$$

$$\tilde{\beta} = \frac{\mathbf{v}}{c},$$

Semi-classical wave function of the photon from an atomic decay

Using the Classical Retarded Propagator

$$\Psi(t,r) = \frac{\Psi_o}{4\pi r} e^{-i(\omega - i/\tau)(t-r/c)} \vartheta(t - r/c)$$

$\tau\ is\ the\ life-time\ of\ the\ photon$

From Classical to Quantum Propagator

$$\boxed{D_{retarded}(t, r) = \frac{1}{4\pi r}\delta(r - ct)}$$

Classically, a photon can be **both** on the light-cone and on the mass-shell

$$\boxed{r = ct \ ; \quad Q^2 = 0}$$

But, not quantum mechanically

Feynman Propagator I

The quantum Feynman propagator is given by

$$D_F(t,r) = \frac{i}{\pi}\int_o^\infty \frac{t' dt' D_{ret}(t-t',r)}{(t-t'-i\epsilon)^2}$$

$$D_F(x-y) = \frac{i}{4\pi^2}\left(\frac{1}{(x-y)^2 - i\epsilon}\right)$$

The principal value part is propagation off the light cone

Feynman Propagator II

In momentum space

$$D_F(x-y) = \int (\frac{d^4Q}{(2\pi)^4}) D(Q)$$

$$D(Q) = \frac{1}{Q^2 + i\epsilon} = P\frac{1}{Q^2} - i\pi\delta(Q^2)$$

In coordinate space

$$D(x) = \frac{i}{4\pi^2[x^2 + i\epsilon]} = \frac{1}{4\pi}\delta(x^2) + \frac{i}{4\pi^2}P\frac{1}{x^2}$$

A photon on mass shell can not be on the light cone

A photon on the light cone can not be on mass shell

Bhabha scattering I Annihilation s-channel

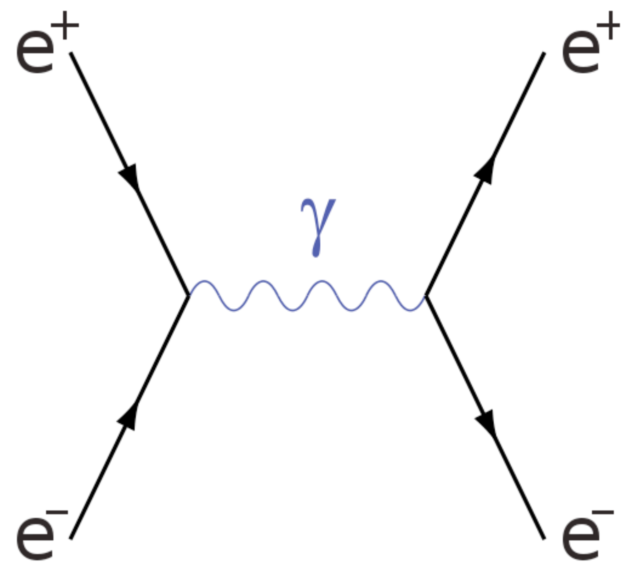
- In the electron-positron CM frame, this s-channel photon is time like with 4-momentum

$$Q^\mu = (\sqrt{s}, \mathbf{0})$$

This photon's classical equation of motion to go from initial position y to final position x is given by

$$x^\mu(\tau) = y^\mu + (\frac{Q^\mu}{\sqrt{s}})c\tau$$

- Distance travelled is r = 0
- The time taken is t = tau
- Not surprising since it is the rest frame of this [massive, off-shell] photon



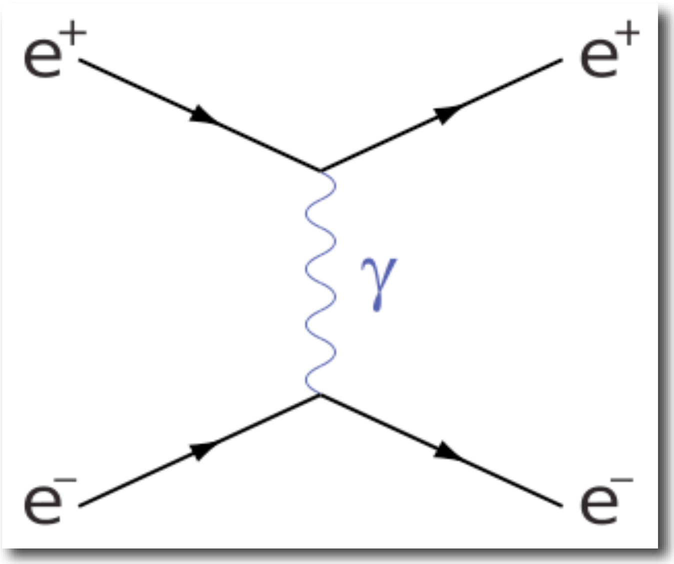
Classical Velocity of the Photon for the Annihilation Channel

1. The classical velocity of this photon [in the vacuum] is zero
2. The above is not possible classically
3. The photon is off mass-shell and off the light cone
4. We do not worry about it because this photon is virtual
5. It is understood that it will connect to some physical final state which is “Classical to a sufficient degree of accuracy”, namely in this case the final pair of electron-positron

Bhabha Scattering II: Scattering t-channel

In the CM frame, the t-channel photon is space like with its 4-momentum

$$Q^{\mu} = (0, \mathbf{Q})$$



This photon's classical equation of motion to go an invariant length L from y to x

$$x^{\mu}(L) = y^{\mu} + (\frac{Q^{\mu}}{\sqrt{-t}})L$$

In this frame the distance travelled r = L and time taken t = 0.

Classical Velocity of the Photon for the Scattering Channel

1. The classical velocity of the photon in this frame is infinite
2. There is no rest frame: space-like photon speed in any frame is greater than c
3. The energy of the photon is strictly zero [in the CM frame]
4. This photon is clearly off its mass-shell and off the light cone which is not possible classically
5. We are not worried because we know that there is a final electron positron state to which it will emerge
6. The one thing peculiar about space-like events is the lack of temporal ordering, namely there would exist another frame where y goes to x.
7. Point 6 is physically moot for a photon which is its own anti-particle but in OPERA a muon neutrino goes from CERN to Gran Sasso; in some other frame, an anti-neutrino goes the other way.

Evidence of Quantum Behavior from Bhabha

Observed Interference between s- and t-channel photons

Classically: addition of probabilities not amplitudes hence no interference

Why the S-matrix ?

Einstein's objections to the quantum theory:

1. EPT (c 1930) [time-like correlations]
2. EPR (c 1934) [space-like correlations]
3. Incompleteness

led Bohr and Heisenberg into a defensive position regarding space-time descriptions of physical phenomena and Heisenberg's brilliant response was to invent the S-matrix (c 1936) from which space-time was entirely eliminated:

$$S = lim_{t_i \to -\infty; t_f \to +\infty} U(t_f; t_i)$$

Guess who wrote the letter to whom

It seems likely to me that quantum mechanics can never make direct statements about the individual system, but rather it always gives only average values

A letter from W. Heisenberg to A. Einstein, February 18, 1926

Letter from A. Einstein to E. Schrodinger, June 17, 1935:

I consider the renunciation of a spatio-temporal setting for real events to be idealistic spiritualistic. This epistemology-soaked orgy ought to come to an end.

No doubt, however, you smile at me and think that, after all, many a young whore turns into an old praying sister, and many a young revolutionary turns into an old reactionary.

R. P. Feynman,
in the Appendix: The relation of real and virtual processes,
Phys. Rev. 80 (1950), page 455,

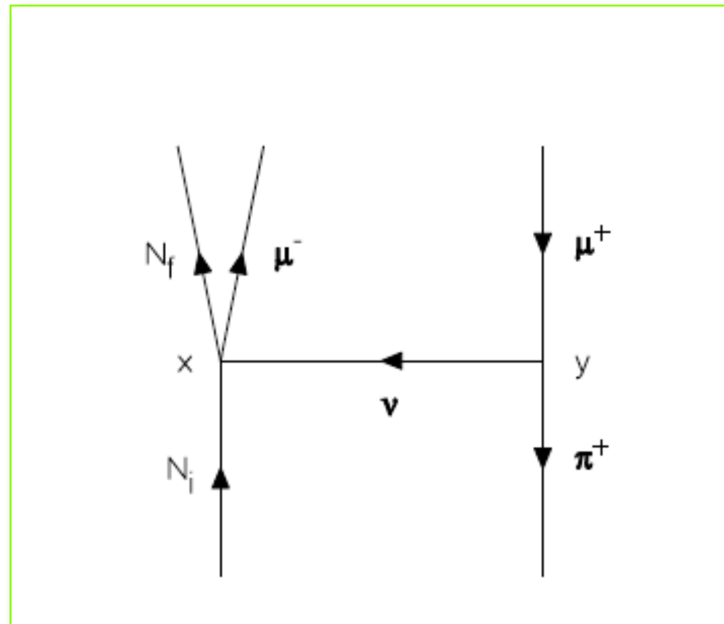
What looks like a real process from one point of view may appear as a virtual process occurring over a more extended time.

Paraphrasing Niels Bohr

In Quantum Mechanics, it is not over until it is all over.

Feynman Diagram for OPERA [not shown to size]

- A positive charged pion decays at y in Geneva [or France] and at x in Gran Sasso a negatively charged muon and a final nucleus is detected



- The entire process

$$\pi^+(P_\pi) + N_i(P_i) \rightarrow \mu^+(p_+) + \mu^-(p_-) + N_f(P_f)$$

Must be considered

Fundamental aspects of MINOS & OPERA

The neutrino experiments of the MINOS & OPERA types, are large realistic versions of the famous Schrodinger cat-alive and cat-dead superposition of states.


DANGER
FALLING ROCKS
DUE TO
PROTON DECAY
S.Harris

Pion-alive and Pion-dead in OPERA

For consider: a pion with a Lorentz factor

$$\gamma_\pi = 300$$

The mean distance of its decay is

$$D = 300 \times (3 \times 10^5 Km/sec.) \times (2.2 \times 10^{-8} sec.) \sim 2Km$$

Unless one detects the positive muon, one has simply no way of knowing whether the pion is alive or dead, that is one has no way of knowing when the virtual neutrino was born

Neutrino amplitude

$$\Psi(\mathbf{x},t) = \int (d^3\mathbf{x}^{'})(cdt^{'})\delta[L^2 - (\mathbf{x}-\mathbf{x}^{'})^2 + c^2(t-t^{'})^2] s_{in}(\mathbf{x}^{'},t^{'})$$

$$s_{in}(\mathbf{x}^{'},t^{'}) = s_o e^{i\mathbf{Q}\cdot\mathbf{x}^{'}} e^{-iEt^{'}/\hbar} \delta^3(\mathbf{x}^{'})\vartheta(t^{'})\vartheta(T-t^{'})$$

$$\Psi(r,t) = (\frac{s_o}{2cr}) \int_o^T (dt^{'}) e^{-iEt^{'}/\hbar} \delta[t^{'} - \{t - \frac{r}{c}(1 - \frac{L^2}{2r^2})\}]$$

$$|\Psi(r,t)|^2 = (\frac{s_o}{2cr})^2 \vartheta(t - \frac{r}{c} - \Delta t)\vartheta(T - \{t - \frac{r}{c} - \Delta t\})$$

The final time shifted intensity

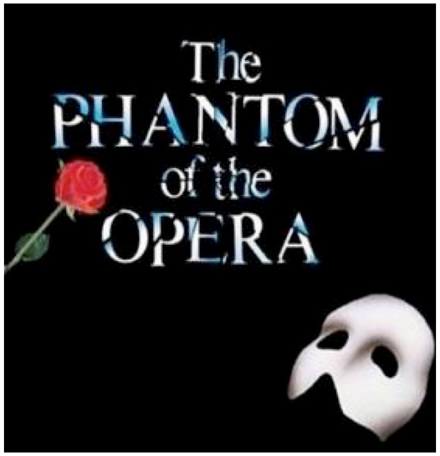
OPERA space-like values

$$\frac{L}{r} = \frac{\mu c}{|\mathbf{Q}|}$$

$$\mu c \sim 200\ MeV/c$$

$$|\mathbf{Q}| \sim 20\ GeV/c$$

$$r = 730\ Km$$



$$L \sim 5\ Km$$

$$\Delta t = -\frac{L^2}{2rc} \approx -55\ ns$$

Simple estimate of the mean neutrino virtual mass

Consider a pion decay at rest into a muon and an off-shell neutrino

$$\pi^+(P_\pi) \to \mu^+(p_+) + \nu_\mu(k)$$

Energy momentum conservation gives

$$m_\pi = \sqrt{m_\mu^2 + \mathbf{k}^2} + \sqrt{\mathbf{k}^2 - Q^2}$$

Thus, the virtual neutrino mass

$$Q_{max} = \sqrt{m_\pi^2 - m_\mu^2} \sim 100 MeV$$

Mean Virtual Mass of the Neutrino in OPERA

We have a prediction: Based on their timing measurements OPERA

Should find a momentum transfer of about - 0.04 $(GeV/c)^2$

$$Q^2 = -t = -(P_\pi - p_+)^2$$

$$Q^2 = -t = -(P_f + p_- - P_i)^2$$

$$< Q^2 > \approx \; (200 \; MeV/c)^2$$

Neutrino Telecommunications I

Matin Durrani, Deputy Editor of New Scientist discussed a Neutrino Telecommunications project by Pirelli Labs in the 182 issue 2443 - 17 April 2004, page 36.

F. Fontana, the head of Pirelli research was quoted as saying that he believed in the feasibility of the project through detection of neutrinos by Weber's sapphire crystals and added that

" .....calculations by theorists Allan Widom from Northeastern University in Boston and Yogi Srivastava from the University of Perugia in Italy, confirm that stiff crystals should be able to detect neutrinos".

Neutrino Telecommunications II

Of course, we had done no such calculations and certainly not in 2004 the day of the interview.

But the point to notice is that thanks to the superluminal nature of neutrino communications, our only work on neutrino telecommunication done in the year 2011 could be reported 7 years earlier, in the year of our Lord 2004.

Amen.

Suggested but never realized EPR & EPT Superluminal experiments for QED

Quantum Electrodynamic Processes In Electrical Engineering Circuits.
Y. Srivastava, A. Widom, **Phys.Rept.148:1-65,1987**.

Past, future and elsewhere in quantum mechanics.
Y. Srivastava, A. Widom, E. Sassaroli,
Published in *Rome 1994, Phenomenology of unification from present to future* 265-276 (1994)

Acausal behavior in quantum electrodynamics.
A. Widom, Y.N. Srivastava, E. Sassaroli
International Conference on Quantum Coherence, Boston, World Scientific (1997). e-Print: **quant-ph/9802056**

Suggested but never realized EPR & EPT Superluminal experiments for DAPHNE

1. Interference between past and future events in phi ---> k anti-K decays.
Y. N. Srivastava and A. Widom, Phys.Lett.B314:315-319,1993.
2. Real and virtual strange processes.
Y. N. Srivastava, A. Widom and E. Sassaroli
e-Print: **hep-ph/9507330**
3. Comment on 'EPR without 'collapse of the wave functions' '.
Y. N. Srivastava, A. Widom and E. Sassaroli:
e-Print: **hep-ph/9511294**
4. Spatial correlations in two neutral kaon decays.
Y. N. Srivastava, A. Widom and E. Sassaroli:
Z.Phys.C66:601-605,1995.

Possible Experiments for Super B

Conclusions and open Questions

1. Special theory of relativity is alive and well: MINOS & OPERA confirm it
2. No ordering of time for space-like events: in our frame a muon neutrino went from CERN to Gran Sasso; in another frame an anti neutrino went from Gran Sasso to CERN.
3. Mass of the neutrino ?
4. How long does a tau neutrino born as a muon neutrino take ?
5. Tantalizing opportunities for Super B

6. Supernova1987A: Time of Arrival of Neutrinos versus that of the Photon

Thank you