Superluminal group velocities of tunneling photons

"Starring Maxwell's equations and the Wigner tunneling time"

George Soli (Integrated Detector Systems)
Morley Blouke (Scientific Imaging Technologies)

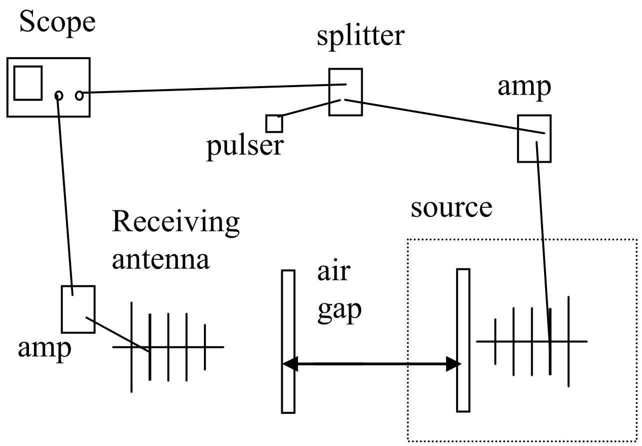
The superluminal group velocity of tunneling photons is measured and found to be asymptotically defined by Maxwell's equations and the Wigner tunneling time, $\Delta\tau = d\phi / d\omega = \hbar\, d\phi / dE$ where $E = \hbar\omega$ and ϕ is the transmitted phase. The asymptotic tunneling time is true only after the time domain resonance has faded out (the reflected wave has finished destructively interfering with the tale of the tunneled wave). The experiment uses two-meter wavelength photons tunneling through a water mirror that is constructed using two water tanks. The time domain resonance is measured as "over the barrier" transmission through an anti-reflective water tank system. The program used to compute the measured tunneling data was also used to design the anti-reflection coating on the CCDs in the advanced camera for surveys on the Hubble space telescope. The physics can be compared to massive particle tunneling that uses the time-dependent Schrodinger equation *. A measurable consequence of superluminal energy flow is the possible sidereal equivalence of superluminal group velocity to the cosmic-microwave-background preferred reference frame **. This requires two-meter wavelength photons.

* G. Garcia-Calderon, and J. Villavicencio, "Delay time and tunneling transient phenomena", arXiv:quant-ph/0210008 01 Oct 2002.
** S. Liberati, S. Sonego, and M. Visser, "Faster-than-c signals, special relativity, and causality", arXiv:gr-qc/0107091 27 Jul 2001.

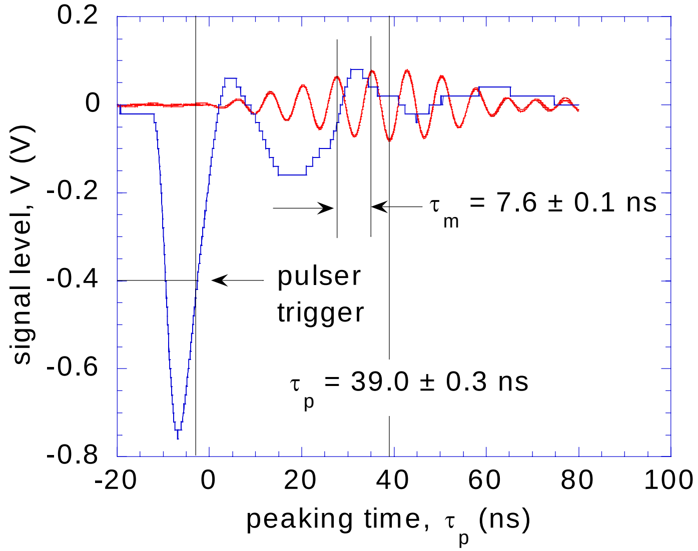
Comparing this experiment to the Berkeley (UCB) experiment [1].

Experiment	UCB	IDS
Wavelength	700 nm	2000 mm
Bandwidth in wavelength	6 nm	100 mm
Wavepacket time width	20 fs	80 ns
Mirror length	1.1 μm	2.2 m

[1] R. Y. Chiao, “Tunneling Times and Superluminality: a Tutorial”, quant-ph/ 9811019, 7 Nov 1998. At LANL.



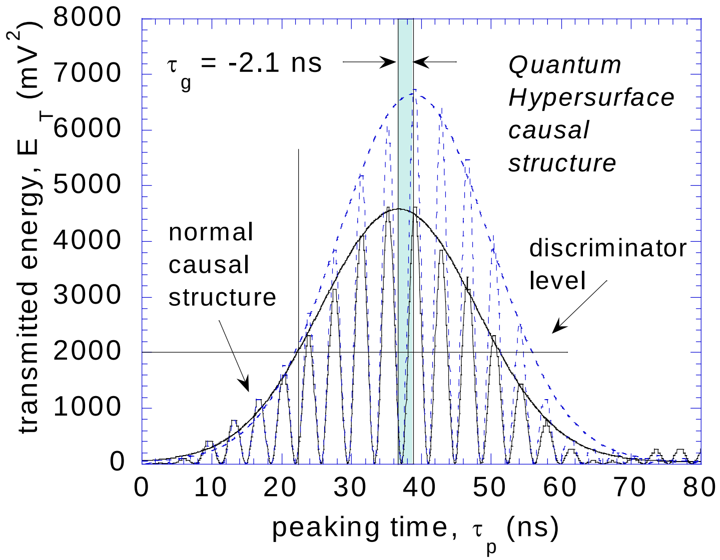
- The Berkeley experiment, by measuring one photon at a time, enables the wavepacket interpretation used here.
- The mirror in this experiment consists of two Plexiglas water tanks. The water layer thickness in each tank is 12.7 mm or one-half inch. The water tanks are constructed with quarter inch thick Plexiglas and are 4 feet wide (along the folded dipole direction) and two feet high.
- The drawing shows the experiment setup with the air-gap length L between the water tanks and the source including its water tank and transmitting antenna**.**
- The transmitting and receiving antennas are identical five-element folded-dipole Yagi antennas designed for two-meter wavelength radio waves.
- The scope is a Tektronix™ TDS220. The pulser is a Phillips Scientific™ Model 417 NIM Pocket Pulser. The amps are from RadioShack™ catalog number 15-1140.



Peak to peak separation time starting from the left side of the figure including the value shown in the figure.

peak numbers	τ_m (ns)	wavelength (cm)
1 to 2	6.8	204
2 to 3	6.8	204
3 to 4	7.2	216
4 to 5 (shown)	7.6 ± 0.1	228
5 to 6 and 6 to …	7.6	228

- Five source-wavepacket data sets are shown in the figure. Each data set contains 128 samples, averaged by the scope. All error bars are the standard deviation of five data set measurements.
- The source data is taken with only the water tank closest to the source in place.
- The 7.6 ± 0.1 ns peak to peak time, τ_m, gives a 228 cm photon wavelength, the cut-off wavelength. Each antenna is surrounded by aluminum screen, except for an opening that is 114 cm wide (along the folded dipole direction), which effectively cuts off the signal wavelength at 228 cm.
- The peak to peak separation times are listed in the table showing that the higher energy components are in the front part, or near the wavefront, of the wavepacket.
- The peaking time, τ_p, of 39.0 ± 0.3 ns is relative to the pulser and one pulser data set is shown. The pulser scope trigger is rising edge set at –0.4 volts.

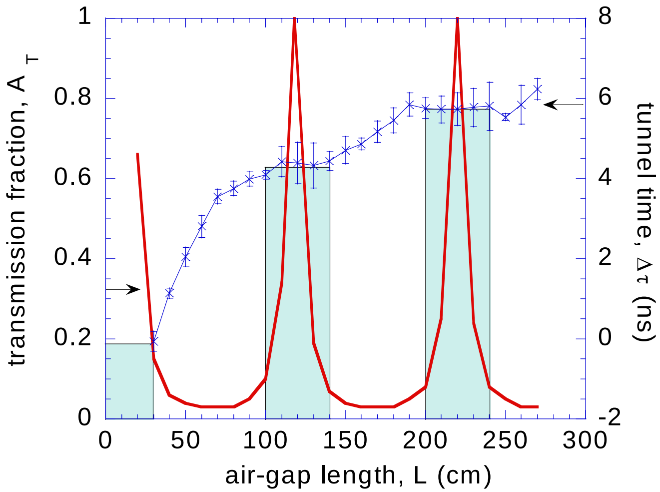


Scope source and L = 220 cm data sets showing the peaking times and the means and standard deviations.

128 sample data sets averaged by the scope	Source $(\tau_P)_{SOURCE}$ ns	L = 220 cm τ_P ns
Data set 1	38.828	37.646
Data set 2	38.741	37.146
Data set 3	38.880	36.758
Data set 4	39.544	37.730
Data set 5	38.818	37.518
Mean	38.962	37.360
Standard deviation	0.32901	0.40369

- The special theory of relativity restricts quanta to have wavefronts that travel at the vacuum speed of light even in materials. This effect is measured with the source and tunneled wavefronts arriving simultaneously at the oscilloscope, at about zero peaking time. Space-time has a Minkowski causal structure near the wavefronts [2].
- The – 2.1 ns negative group delay time shown in the figure is from data set number 3 in the table. This data set is shown in the figure with Gaussian fits to the measured voltage squared. The amplitude of the fits are doubled to enclose the peaks. The peaking times listed in the table are the peaks of the Gaussian fits.
- The Quantum *foliation* Hypersurface exists only above a discriminator level.

[2] C. Will, "Clock synchronization and isotropy of the one-way speed of light", Phys. Rev. D 45, 403 (1992).

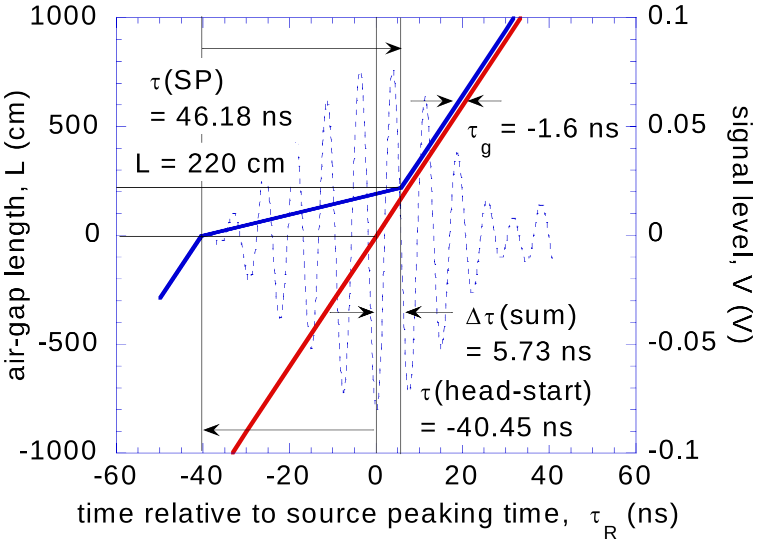


Scope wavepacket peaking time, τ_p, the group-delay time, τ_g, with propagated errors, and the tunnel time, $\Delta\tau$.

L (cm)	τ_p (ns)	τ_g (ns)	$\Delta\tau$ (ns)
source	38.96 ± 0.33	----	----
200	38.05 ± 0.26	-0.91 ± 0.42	5.75 ± 0.42
210	37.69 ± 0.33	-1.27 ± 0.47	5.73 ± 0.47
220	37.36 ± 0.40	-1.60 ± 0.52	5.73 ± 0.52
230	37.07 ± 0.48	-1.89 ± 0.58	5.77 ± 0.58
240	36.77 ± 0.60	-2.19 ± 0.68	5.80 ± 0.68

- The measured peaking time difference, $\tau_g = \tau_p - (\tau_p)_{SOURCE}$, is defined as the measured group delay time, τ_g [1].
- The measured tunnel time shown, is $\Delta\tau = (L/c) + \tau_g$ where, (L/c), is the source time.
- The transmission fraction is for the wavefront wavelength of 204 cm.
- The asymptotically defined Wigner tunneling time, $\Delta\tau = d\phi / d\omega = \hbar\, d\phi / dE$ where $E = \hbar\omega$ and ϕ is the transmitted phase. This is the tunneling time after the time domain resonance has died out.
- The group velocity v(group) = $d\omega / dk$ is asymptotic and k is the wave number.
- This implies that $\Delta\tau = d\phi / d\omega$ because the air-gap L = v(group) $\Delta\tau = (d\omega / dk)(d\phi / d\omega) = d\phi / dk$, and $d\phi = L\, dk$ equals the phase acquired by the transmitted wave.
- The time domain resonance is a metastable state. At a 204 cm wavelength and at L = 220 cm, the change in frequency at FWHM in the transmission amplitude is $\Delta\omega$ = 4.5E7 rad/sec, and $\Gamma = \hbar\, \Delta\omega$ = 4.75E-20 ergs.
- The tunneling time is $\Delta\tau = 2\, \hbar / \Gamma$ = 44.4 ns. (see Breit-Wigner formula [3])

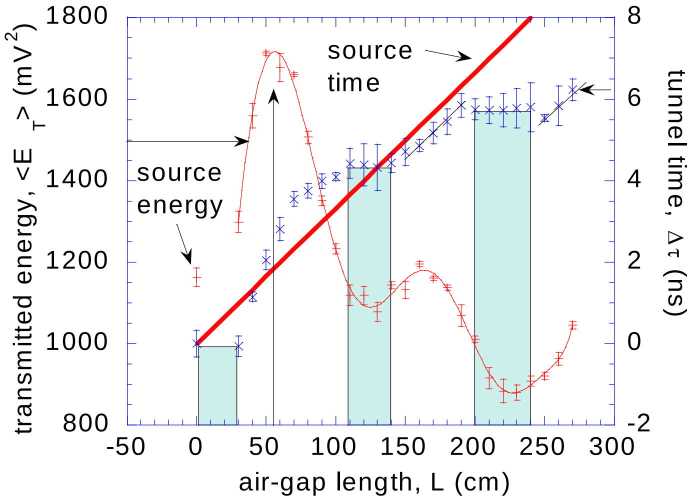
[3] C. Joachain, Quantum Collision Theory, North-Holland, 1983.



A tunneling model is defined showing that wavepacket reconstruction information is not superluminal [1]. At an air-gap length of 220 cm however, the wavepacket energy advances 1.6 ns. The transmission fraction and transmission phase are computed in Mathcad™, with a program described in reference [4] appendix C. The steepest slope of the bold lines in the figure is the vacuum speed of light thus showing that wavepacket reconstruction information is subluminal but has a head-start. The photon phase velocity $v_p = E/p$, the group velocity $v_g = dE/dp$, and the Reconstruction Information velocity $v(RI) = L / \tau(SP)$ and is subluminal. $\tau(SP) = 2\,\hbar / \Gamma = 44.4$ ns ≈ 46.18 ns.

- The Stationary Phase tunnel time, $\tau(SP) = d\phi/d\omega$, where ϕ is the transmitted photon phase, added to the head start time, τ(head-start), equals the tunnel time data, $\Delta\tau$(sum).
- This effect is caused by selecting wavepacket components near the wavefront.
- The head-start time is defined graphically in the figure. For an air-gap length of 220 cm, the transmission fraction of a 204 cm wavelength photon is 0.997 and the wavepacket front is being actively selected.
- The computed stationary phase tunnel time for 204 cm wavelength photons, is $\tau(SP) = 46.18$ ns, its peak value. The head-start time is defined as, $\tau(\text{head-start}) = \Delta\tau(\text{sum}) - \tau(SP) = -40.45$ ns, where $\Delta\tau(\text{sum}) = 5.73$ ns, the measured tunneling time.
- The head-start time also equals the group delay time minus the source peaking time, $\tau(\text{head-start}) = \tau_g - (\tau_P)_{SOURCE} = -40.56$ ns, giving a model error of 0.11 ns.

[4] J. Rancourt, Optical Thin Films User Handbook, SPIE Optical Engineering Press, 1996, Appendix C.



The flat tops of the boxes shown in the Figure identify regions where the tunneling time is independent of the tunnel length. This is the Hartman effect [1]. The asymptotic tunneling time saturates at the minimums in the transmitted energy and is a constant given by the time-energy Heisenberg uncertainty principle, $\Delta\tau = \hbar/\Delta E$, where the energy, ΔE, must be "paid back" in a time less than $\Delta\tau$, regardless of the energy flow speed or group velocity required to do so.

- Superluminal group velocities can be understood in terms of subluminal metastable states that are resonance's in the time domain defined by the Breit-Wigner formula [3]. The metastable states have lifetimes defined by the time-energy Heisenberg uncertainty principle and are computable using *only* Maxwell's equations.
- The transmitted energy, E_T (mV^2), averaged over time, $\langle E_T \rangle$, from 0 to 80 ns, is maximum at an air-gap length of 57 cm, and this is identified as a 228 cm photon quarter wavelength.
- Superluminal group velocities happen at the minimum in the transmitted energy, in a Bragg mirror, where most of the energy is reflected.
- This happens at the "stop-band" computed using Maxwell's equations where the superluminal group velocity is asymptotically defined by the Wigner tunneling time, $\Delta\tau = d\phi \,/\, d\omega = \hbar\, d\phi \,/dE$ where $E = \hbar\omega$ and ϕ is the transmitted phase.
- The asymptotic tunneling time is true only after the time domain resonance has faded out (the reflected wave has finished destructively interfering with the tale of the tunneled wave).

Conclusions

The superluminal group velocity of tunneling photons is measured and found to be asymptotically defined by Maxwell's equations and the Wigner tunneling time, $\Delta\tau = d\phi / d\omega = \hbar\, d\phi / dE$ where $E = \hbar\omega$ and ϕ is the transmitted phase.

> Chiao writes in [1], "The result is simple: this tunneling time is the derivative of the phase of the tunneling amplitude with the respect to the energy of the particle."

The physics can be compared to massive particle tunneling that uses the time-dependent Schrodinger equation *.

> Garcia-Calderon writes in *, "We corroborate that this dynamical *delay time* is accurately described by the analytical expression obtained from the phase energy-derivative of the transmission amplitude."

The asymptotic tunneling time is true only after the time domain resonance has faded out (the reflected wave has finished destructively interfering with the tale of the tunneled wave).

Prelude

A measurable consequence of superluminal energy flow is the possible sidereal equivalence of superluminal group velocity to the cosmic-microwave-background preferred reference frame **. This requires two-meter wavelength photons.

* G. Garcia-Calderon, and J. Villavicencio, "Delay time and tunneling transient phenomena", arXiv:quant-ph/0210008 01 Oct 2002.
** S. Liberati, S. Sonego, and M. Visser, "Faster-than-c signals, special relativity, and causality", arXiv:gr-qc/0107091 27 Jul 2001.