# Question #1

How does wavelength of a photon change with momentum?

(a) The wavelength is proportional to the momentum.

(b) The wavelength is proportional to the square of the momentum.

(c) The wavelength is proportional to the inverse of the momentum.

(d) The wavelength is proportional to the inverse of the square of the momentum.

(e) This is a trick question; the photon is a particle and does not have a wavelength.

# Question #2

How does wavelength of an electron change with momentum?

(a) The wavelength is proportional to the momentum.

(b) The wavelength is proportional to the square of the momentum.

(c) The wavelength is proportional to the inverse of the momentum.

(d) The wavelength is proportional to the inverse of the square of the momentum.

(e) This is a trick question; the electron is a particle and does not have a wavelength.

# Interference with Photons

We know that light must be a wave because it has interference properties.

We know that light must be composed of particles because of the thermal spectrum, Compton effect, and photoelectric effect.

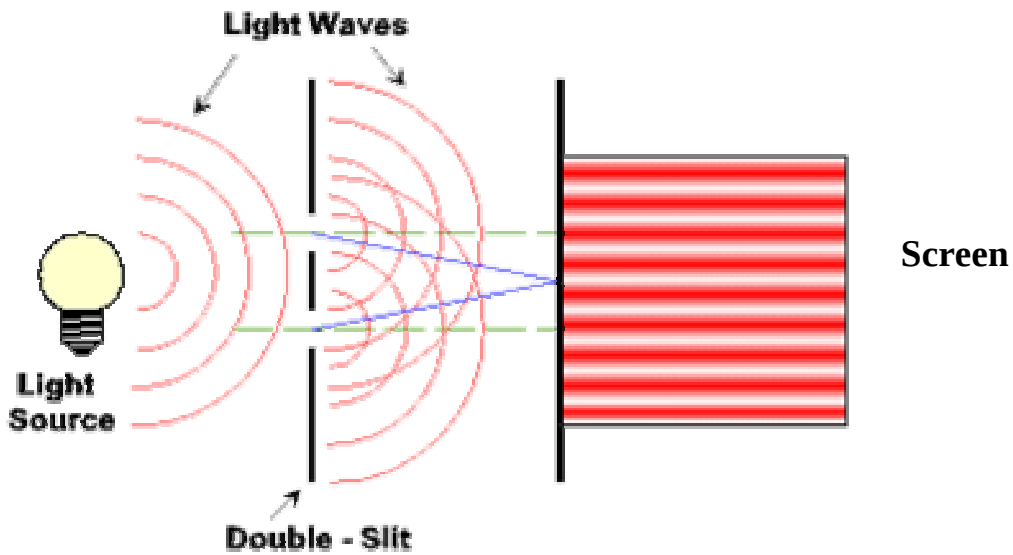
Which one is correct?

How can both be correct?

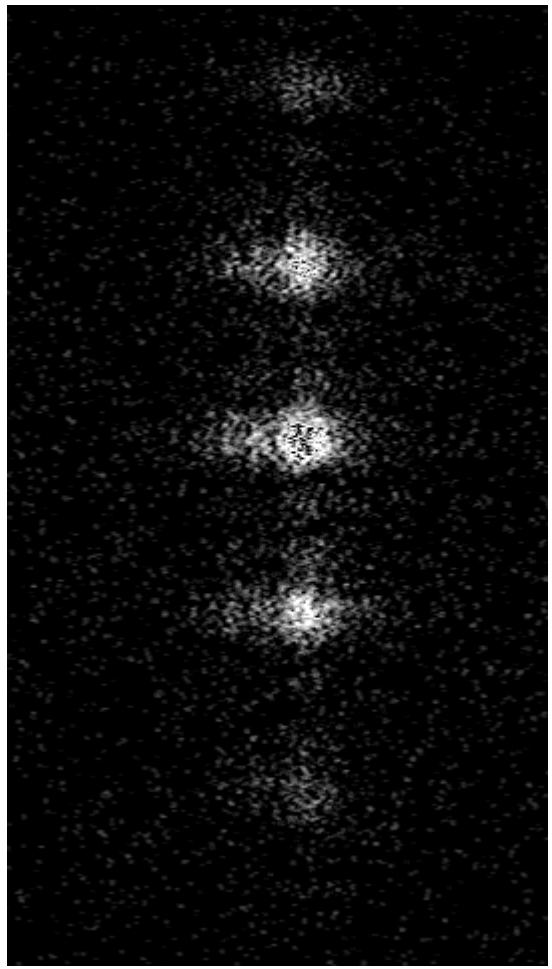
No one else knows either.

# Interference with Light Waves

Qualitatively, how does interference between waves work?
What is the condition for constructive interference?
What is the condition for destructive interference?
What happens if you cover 1 hole?
What pattern do you expect if particles go through the holes?
What pattern do you expect if perpendicular polarizer behind each hole?



# Wave Particle Duality



1/30 sec (5 phot) 1 sec (150 phot) 100 sec (15,000 phot)

http://ophelia.princeton.edu/~page/single_photon.html

# How can we explain?

Information

A single photon goes through at a time.

If you cover one of the holes, get a different pattern.

If you put perpendicular polarizers behind each hole, you don't get interference?

Assumption is that each photon (particle) has a wave associated with it. The wavelength of the wave is given by $\lambda = h/p$ and the frequency of the wave is $f = E/h$.

# de Broglie waves

**ALL** particles have a wave associated with them!!!

The wavelength is given by $\lambda = h/p$ and the frequency is given by $f = E/h$.

Why don't we notice?

An object has v = 1 m/s and M = 1 kg. Compute the wavelength and frequency.

$\lambda = h/p = 6.6 \text{ X } 10^{-34} \text{ J s}/(1 \text{ kg X } 1 \text{ m/s}) = 6.6 \text{ X } 10^{-34} \text{ m}$

$f = E/h = (\frac{1}{2}\ 1 \text{ kg } 1 \text{ m}^2/\text{s}^2)/6.6\text{X}10^{-34} \text{ J s} = 1.5 \text{ X } 10^{33} \text{ Hz}$

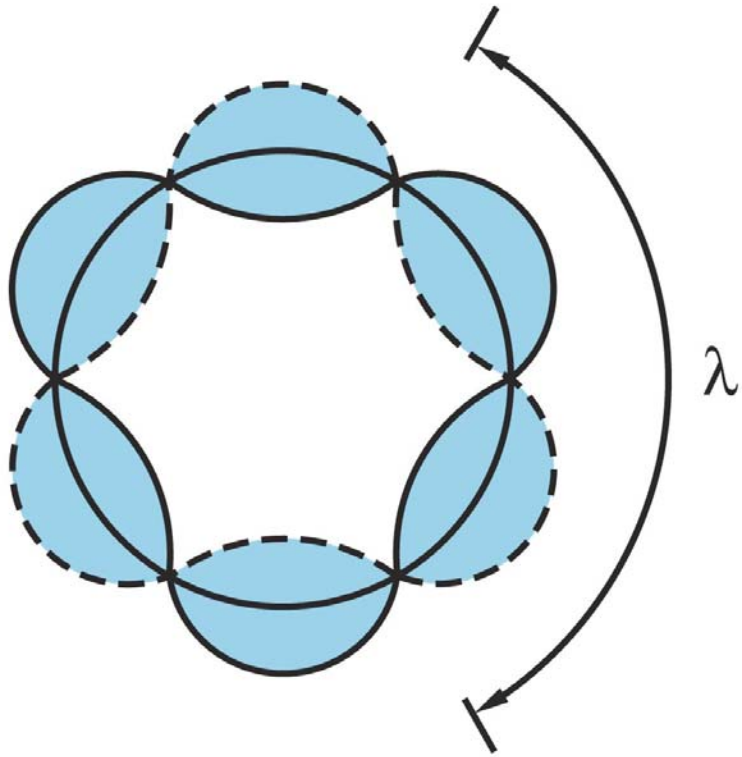
# Evidence

Bohr condition:

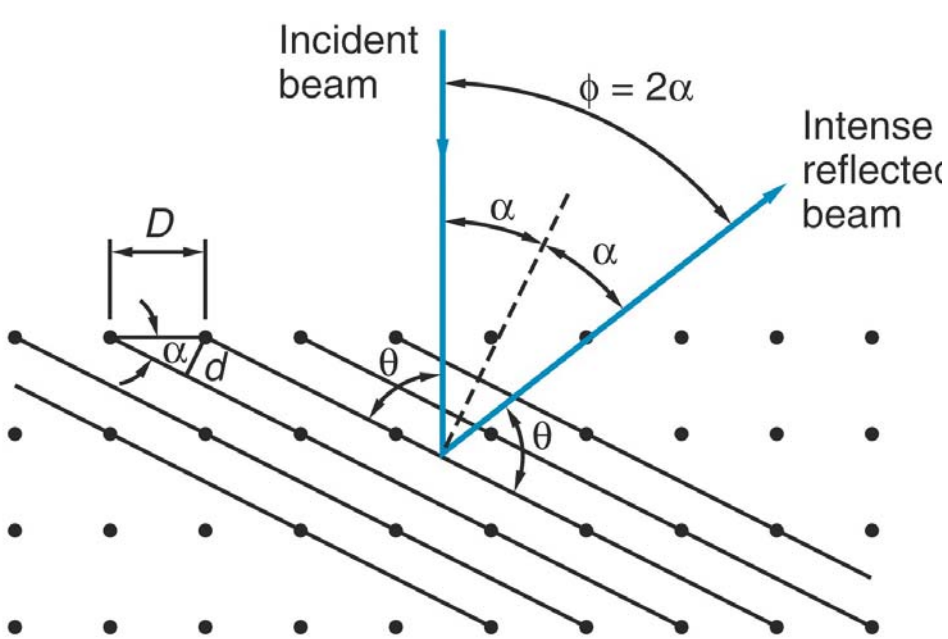
$L_n = m\,v\,r = n\,h/2\,\pi \quad \Rightarrow \quad 2\,\pi\,r = n\,h / m\,v = n\,\lambda$

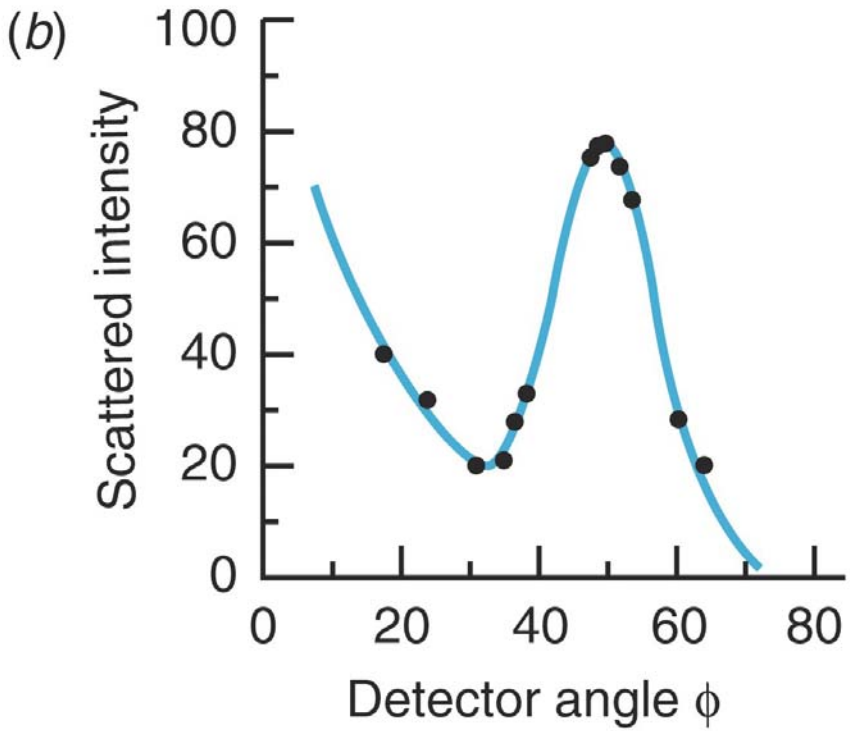
Circumference equals integer number of wavelengths.

Standing wave!



# Scattering of Electron by Crystal



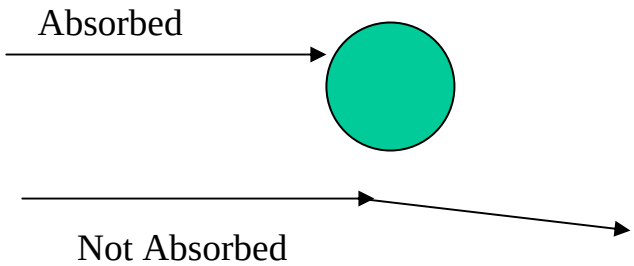



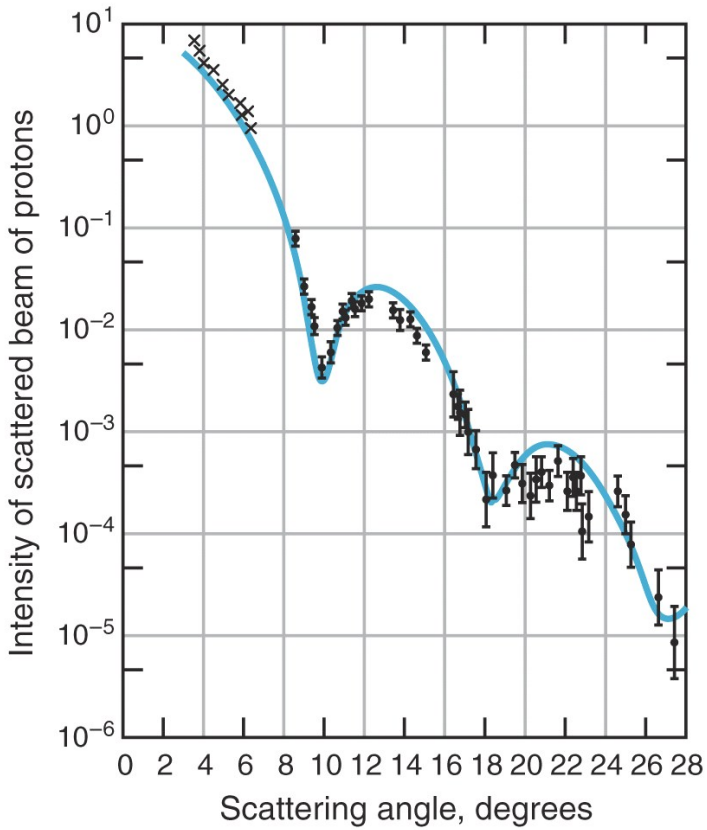

Why does a regular array of scatters give constructive interference?

# Proton-Nuclei Scattering

From Rutherford, shouldn't we get simple decreasing function?

What are the dips from?



# Adding Many Waves

Make a wave at (t=0) by adding

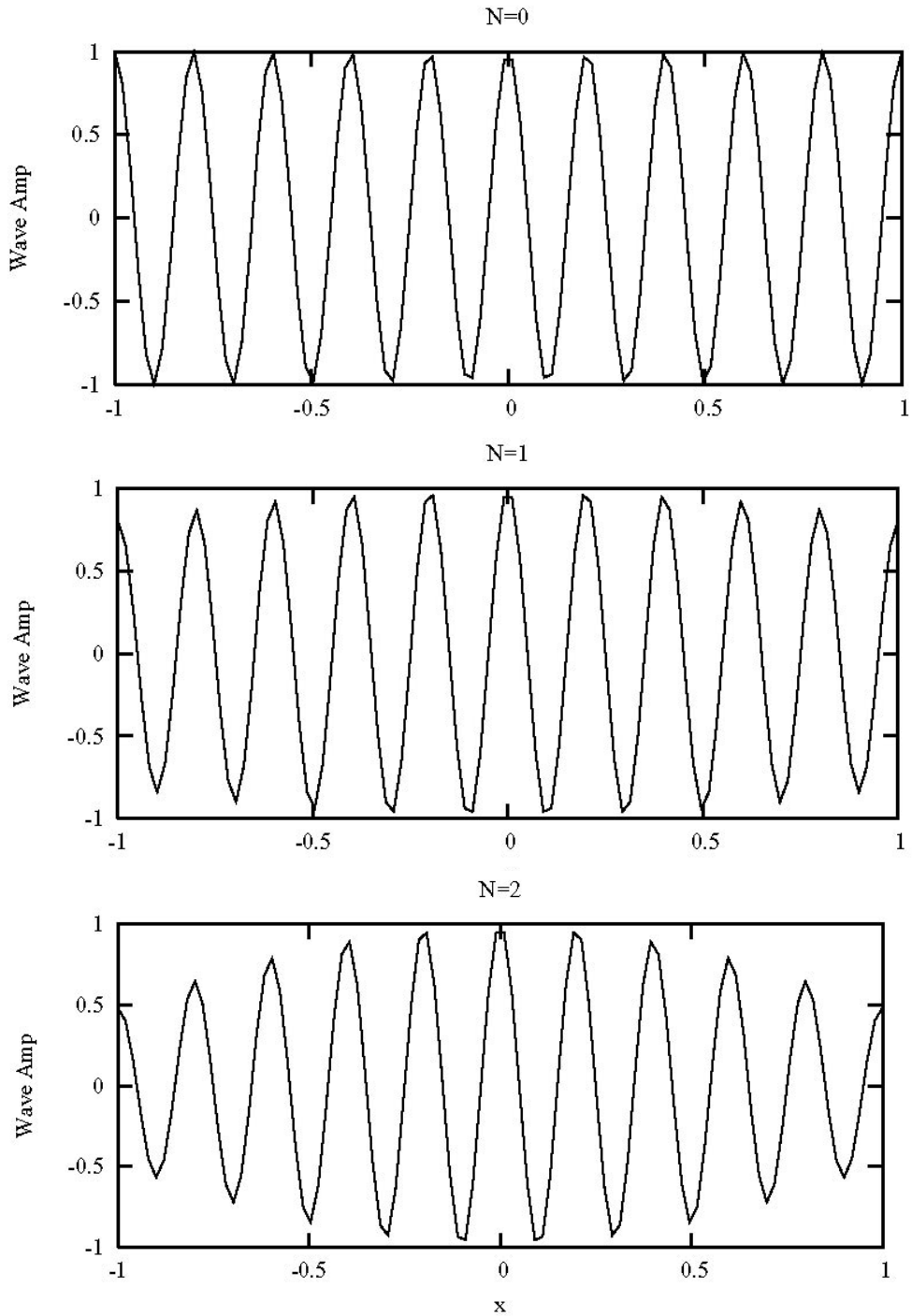
$\{\cos[k\,x] + \cos[(k+\Delta k)x] + \cos[(k-\Delta k)x] + \cos[(k+2\Delta k)x] + \cos[(k-2\Delta k)x] + \ldots\}/N$

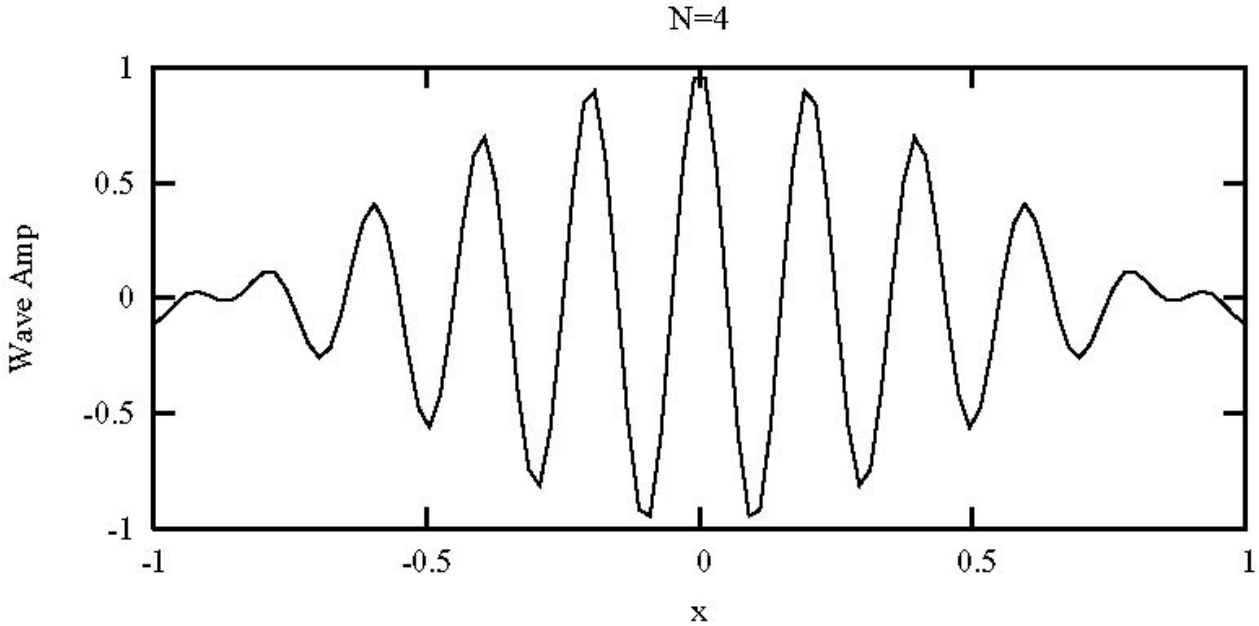
What will this look like as number of terms increase?

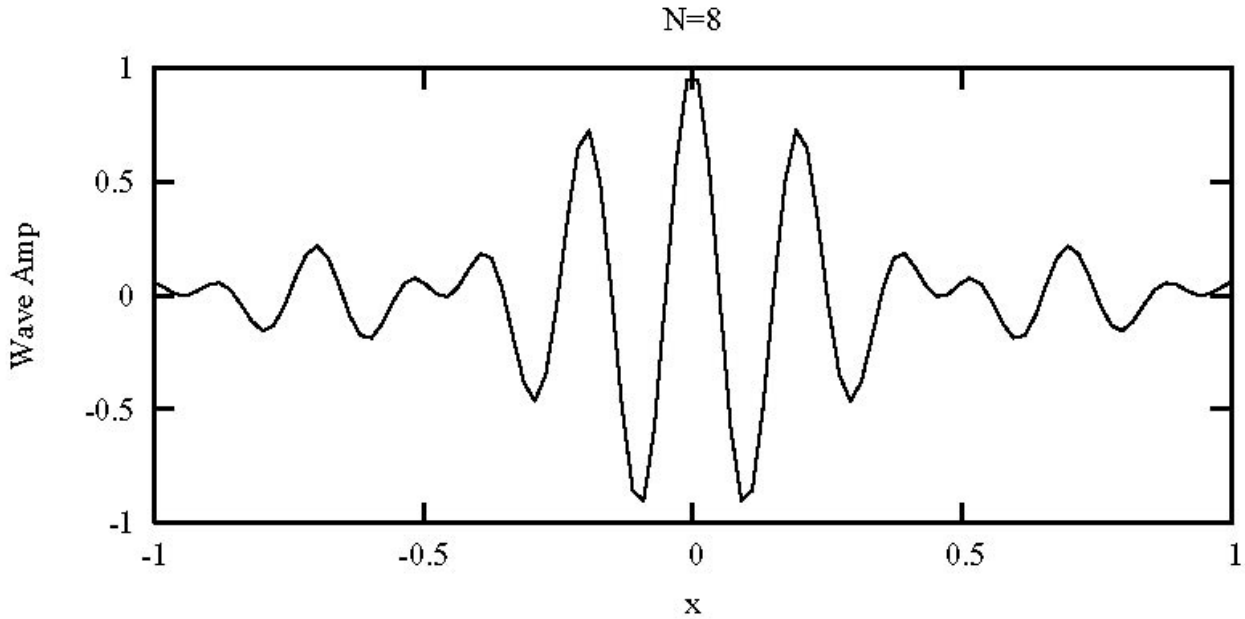
Specific calculation with $k = 10\,\pi$ and $\Delta k = \pi/4$

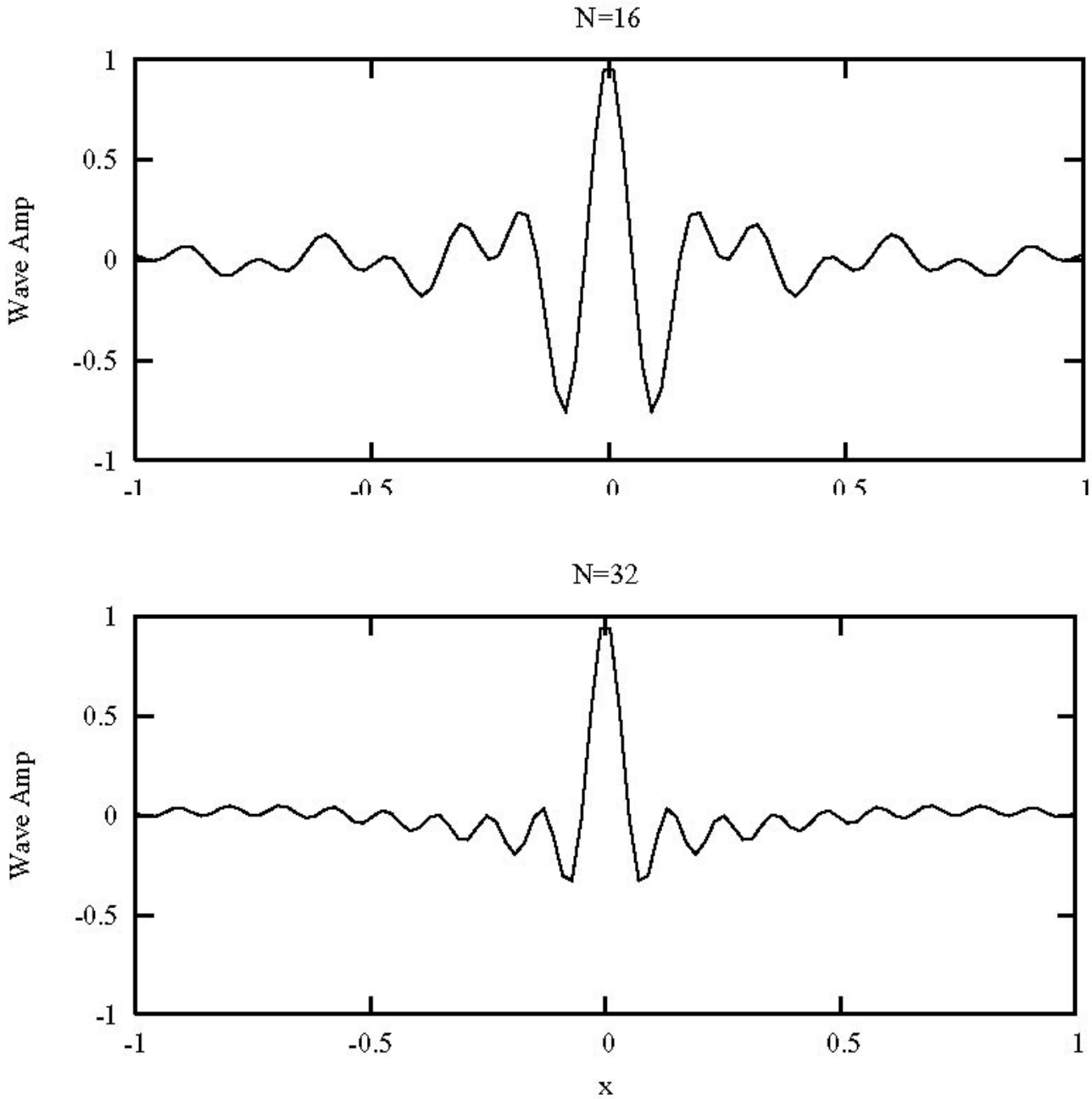
Not important but can get simple expression for sum

$\text{Sum} = \cos[kx]\,\sin[(2N+1)\,\Delta k\,x/2]/\{(2N+1)\,\sin[\Delta k\,x/2]\}$


N=0
Wave Amp
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
N=1
Wave Amp
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
N=2
Wave Amp
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
x


N=4
Wave Amp
x
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1


N=8
Wave Amp
x
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1


N=16
Wave Amp
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
N=32
Wave Amp
1
0.5
0
-0.5
-1
-1
-0.5
0
0.5
1
x