

$$(ii) E = \sqrt{(13.252)^2 + (8.19)^2} \times 10^{-14} \text{ J} = 15.579 \times 10^{-14} \text{ J}$$

$$E = \frac{E_0}{\sqrt{1 - v^2/c^2}} \quad \text{or} \quad 1 - \frac{v^2}{c^2} = \left(\frac{E_0}{E}\right)^2$$

$$v = \left[1 - \left(\frac{E_0}{E}\right)^2\right]^{1/2} c = \left[1 - \left(\frac{8.19}{15.579}\right)^2\right]^{1/2} (3 \times 10^8 \text{ m s}^{-1}) \\ = 0.851c$$

The group velocity will be the same as the particle velocity. Hence,

$$v_g = 0.851c$$

$$\text{Phase velocity } v_p = \frac{c^2}{v} = \frac{c}{0.851} = 1.175c$$

2.39 The position of an electron is measured with an accuracy of 10^{-6} m. Find the uncertainty in the electron's position after 1 s. Comment on the result.

Solution. When $t = 0$, the uncertainty in the electron's momentum is

$$\Delta p \geq \frac{h}{2\Delta x}$$

Since $p = mv$, $\Delta p = m \Delta v$. Hence,

$$\Delta v \geq \frac{h}{2m\Delta x}$$

The uncertainty in the position of the electron at time t cannot be more than

$$(\Delta x)_t = t\Delta v \geq \frac{ht}{2m\Delta x} \\ = \frac{(1.054 \times 10^{-34} \text{ J s}) 1 \text{ s}}{2(9.1 \times 10^{-31} \text{ kg}) 10^{-6} \text{ m}} = 57.9 \text{ m}$$

The original wave packet has spread out to a much wider one. A large range of wave numbers must have been present to produce the narrow original wave group. The phase velocity of the component waves has varied with the wave number.

2.40 If the total energy of a moving particle greatly exceeds its rest energy, show that its de Broglie wavelength is nearly the same as the wavelength of a photon with the same total energy.

Solution. Let the total energy be E . Then,

$$E^2 = c^2 p^2 + m_0^2 c^4 \cong c^2 p^2$$

$$p = \frac{E}{c}$$

$$\text{de Broglie wavelength } \lambda = \frac{h}{p} = \frac{hc}{E}$$

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