37

RELATIVITY

37.1. **IDENTIFY** and **SET UP:** Consider the distance A to O' and B to O' as observed by an observer on the ground (Figure 37.1).

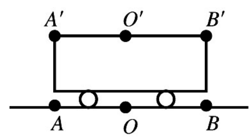


Figure 37.1

EXECUTE: The statement that the events are simultaneous to an observer on the train means that light pulses from A' and B' arrive at O' at the same time. To the observer at O, light from A' has a longer distance to travel than light from B' so O will conclude that the pulse from $A(A')$ started before the pulse at $B(B')$. To the observer at O, bolt A appeared to strike first.

EVALUATE: Section 37.2 shows that if the events are simultaneous to the observer on the ground, then an observer on the train measures that the bolt at B' struck first.

37.2. **IDENTIFY:** Apply $\Delta t = \gamma \Delta t_0$.

SET UP: The lifetime measured in the muon frame is the proper time Δt_0. $u = 0.900c$ is the speed of the muon frame relative to the laboratory frame. The distance the particle travels in the lab frame is its speed in that frame times its lifetime in that frame.

EXECUTE: **(a)** $\gamma = \dfrac{1}{\sqrt{1-(0.9)^2}} = 2.29.$ $\Delta t = \gamma \Delta t_0 = (2.29)\,(2.20\times10^{-6}\text{s}) = 5.05\times10^{-6}$ s.

(b) $d = v\Delta t = (0.900)(3.00\times10^{8}\text{ m/s})(5.05\times10^{-6}\text{s}) = 1.36\times10^{3}\text{ m} = 1.36\text{ km}.$

EVALUATE: The lifetime measured in the lab frame is larger than the lifetime measured in the muon frame.

37.3. **IDENTIFY** and **SET UP:** The problem asks for u such that $\Delta t_0/\Delta t = \frac{1}{2}$.

EXECUTE: $\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}}$ gives $u = c\sqrt{1-(\Delta t_0/\Delta t)^2} = (3.00\times10^{8}\text{ m/s})\sqrt{1-(\frac{1}{2})^2} = 2.60\times10^{8}$ m/s;

$\dfrac{u}{c} = 0.867.$

EVALUATE: Jet planes fly at less than ten times the speed of sound, less than about 3000 m/s. Jet planes fly at much lower speeds than we calculated for u.

37.4. **IDENTIFY:** Time dilation occurs because the rocket is moving relative to Mars.

SET UP: The time dilation equation is $\Delta t = \gamma\Delta t_0$, where t_0 is the proper time.

EXECUTE: **(a)** The two time measurements are made at the same place on Mars by an observer at rest there, so the observer on Mars measures the proper time.

(b) $\Delta t = \gamma \Delta t_0 = \dfrac{1}{\sqrt{1-(0.985)^2}}(75.0\ \mu\text{s}) = 435\ \mu\text{s}.$

EVALUATE: The pulse lasts for a longer time relative to the rocket than it does relative to the Mars observer.

37.5. (a) IDENTIFY and SET UP: $\Delta t_0 = 2.60\times10^{-8}$ s; $\Delta t = 4.20\times10^{-7}$ s. In the lab frame the pion is created and decays at different points, so this time is not the proper time.

EXECUTE: $\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}}$ says $1-\dfrac{u^2}{c^2} = \left(\dfrac{\Delta t_0}{\Delta t}\right)^2.$

$$\frac{u}{c} = \sqrt{1-\left(\frac{\Delta t_0}{\Delta t}\right)^2} = \sqrt{1-\left(\frac{2.60\times10^{-8}\text{ s}}{4.20\times10^{-7}\text{ s}}\right)^2} = 0.998;\ u = 0.998c.$$

EVALUATE: $u < c$, as it must be, but u/c is close to unity and the time dilation effects are large.

(b) IDENTIFY and SET UP: The speed in the laboratory frame is $u = 0.998c$; the time measured in this frame is Δt, so the distance as measured in this frame is $d = u\Delta t$.

EXECUTE: $d = (0.998)(2.998\times10^8\text{ m/s})(4.20\times10^{-7}\text{ s}) = 126$ m.

EVALUATE: The distance measured in the pion's frame will be different because the time measured in the pion's frame is different (shorter).

37.6. IDENTIFY: Apply $\Delta t = \gamma \Delta t_0$.

SET UP: For part (a) the proper time is measured by the race pilot. $\gamma = 1.667$.

EXECUTE: **(a)** $\Delta t = \dfrac{1.20\times10^8\text{ m}}{(0.800)(3.00\times10^8\text{ m/s})} = 0.500\text{ s}.\ \Delta t_0 = \dfrac{\Delta t}{\gamma} = \dfrac{0.500\text{ s}}{1.667} = 0.300\text{ s}.$

(b) $(0.300\text{ s})(0.800c) = 7.20\times10^7\text{ m}.$

(c) You read $\dfrac{1.20\times10^8\text{ m}}{(0.800)(3\times10^8\text{ m/s})} = 0.500\text{ s}.$

EVALUATE: The two events are the spaceracer passing you and the spaceracer reaching a point 1.20×10^8 m from you. The timer traveling with the spaceracer measures the proper time between these two events.

37.7. IDENTIFY and SET UP: A clock moving with respect to an observer appears to run more slowly than a clock at rest in the observer's frame. The clock in the spacecraft measurers the proper time Δt_0. $\Delta t = 365\text{ days} = 8760\text{ hours}.$

EXECUTE: The clock on the moving spacecraft runs slow and shows the smaller elapsed time. $\Delta t_0 = \Delta t\sqrt{1-u^2/c^2} = (8760\text{ h})\sqrt{1-(4.80\times10^6/3.00\times10^8)^2} = 8758.88\text{ h}.$ The difference in elapsed times is $8760\text{ h} - 8758.88\text{ h} = 1.12\text{ h}.$

EVALUATE: 1.12 h is about 0.013% of a year. This difference would not be noticed by an astronaut, but such measurements are certainly within the capability of modern technology.

37.8. IDENTIFY and SET UP: The proper time is measured in the frame where the two events occur at the same point.

EXECUTE: **(a)** The time of 12.0 ms measured by the first officer on the craft is the proper time.

(b) $\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}}$ gives $u = c\sqrt{1-(\Delta t_0/\Delta t)^2} = c\sqrt{1-(12.0\times10^{-3}/0.150)^2} = 0.997c.$

EVALUATE: The observer at rest with respect to the searchlight measures a much shorter duration for the event.

37.9. IDENTIFY and SET UP: $l = l_0\sqrt{1-u^2/c^2}$. The length measured when the spacecraft is moving is $l = 74.0$ m; l_0 is the length measured in a frame at rest relative to the spacecraft.

EXECUTE: $l_0 = \dfrac{l}{\sqrt{1-u^2/c^2}} = \dfrac{74.0\text{ m}}{\sqrt{1-(0.600c/c)^2}} = 92.5\text{ m}.$

EVALUATE: $l_0 > l$. The moving spacecraft appears to an observer on the planet to be shortened along the direction of motion.

37.10. IDENTIFY and SET UP: When the meterstick is at rest with respect to you, you measure its length to be 1.000 m, and that is its proper length, l_0. $l = 0.3048$ m.

EXECUTE: $l = l_0\sqrt{1-u^2/c^2}$ gives $u = c\sqrt{1-(l/l_0)^2} = c\sqrt{1-(0.3048/1.00)^2} = 0.9524c = 2.86\times10^8$ m/s.

EVALUATE: The needed speed is well beyond modern capabilities for any rocket.

37.11. IDENTIFY and SET UP: The 2.2 μs lifetime is Δt_0 and the observer on earth measures Δt. The atmosphere is moving relative to the muon so in its frame the height of the atmosphere is l and l_0 is 10 km.

EXECUTE: **(a)** The greatest speed the muon can have is c, so the greatest distance it can travel in 2.2×10^{-6} s is $d = vt = (3.00\times10^8 \text{ m/s})(2.2\times10^{-6} \text{ s}) = 660 \text{ m} = 0.66 \text{ km}$.

(b) $$\Delta t = \frac{\Delta t_0}{\sqrt{1-u^2/c^2}} = \frac{2.2\times10^{-6} \text{ s}}{\sqrt{1-(0.999)^2}} = 4.9\times10^{-5} \text{ s}.$$

$d = vt = (0.999)(3.00\times10^8 \text{ m/s})(4.9\times10^{-5} \text{ s}) = 15 \text{ km}$.

In the frame of the earth the muon can travel 15 km in the atmosphere during its lifetime.

(c) $l = l_0\sqrt{1-u^2/c^2} = (10 \text{ km})\sqrt{1-(0.999)^2} = 0.45 \text{ km}$.

EVALUATE: In the frame of the muon the height of the atmosphere is less than the distance it moves during its lifetime.

37.12. IDENTIFY and SET UP: The scientist at rest on the earth's surface measures the proper length of the separation between the point where the particle is created and the surface of the earth, so $l_0 = 45.0$ km. The transit time measured in the particle's frame is the proper time, Δt_0.

EXECUTE: **(a)** $$t = \frac{l_0}{v} = \frac{45.0\times10^3 \text{ m}}{(0.99540)(3.00\times10^8 \text{ m/s})} = 1.51\times10^{-4} \text{ s}.$$

(b) $l = l_0\sqrt{1-u^2/c^2} = (45.0 \text{ km})\sqrt{1-(0.99540)^2} = 4.31 \text{ km}$.

(c) time dilation formula: $\Delta t_0 = \Delta t\sqrt{1-u^2/c^2} = (1.51\times10^{-4} \text{ s})\sqrt{1-(0.99540)^2} = 1.44\times10^{-5} \text{ s}$.

from Δl: $$t = \frac{l}{v} = \frac{4.31\times10^3 \text{ m}}{(0.99540)(3.00\times10^8 \text{ m/s})} = 1.44\times10^{-5} \text{ s}.$$

EVALUATE: The two results agree.

37.13. IDENTIFY: Apply $l = l_0\sqrt{1-u^2/c^2}$.

SET UP: The proper length l_0 of the runway is its length measured in the earth's frame. The proper time Δt_0 for the time interval for the spacecraft to travel from one end of the runway to the other is the time interval measured in the frame of the spacecraft.

EXECUTE: **(a)** $l_0 = 3600$ m.

$$l = l_0\sqrt{1-\frac{u^2}{c^2}} = (3600 \text{ m})\sqrt{1-\frac{(4.00\times10^7 \text{ m/s})^2}{(3.00\times10^8 \text{ m/s})^2}} = (3600 \text{ m})(0.991) = 3568 \text{ m}.$$

(b) $$\Delta t = \frac{l_0}{u} = \frac{3600 \text{ m}}{4.00\times10^7 \text{ m/s}} = 9.00\times10^{-5} \text{ s}.$$

(c) $$\Delta t_0 = \frac{l}{u} = \frac{3568 \text{ m}}{4.00\times10^7 \text{ m/s}} = 8.92\times10^{-5} \text{ s}.$$

EVALUATE: $\frac{1}{\gamma} = 0.991$, so $\Delta t = \gamma\Delta t_0$ gives $\Delta t = \frac{8.92\times10^{-5}\text{s}}{0.991} = 9.00\times10^{-5}$ s. The result from length contraction is consistent with the result from time dilation.

37.14. IDENTIFY: The astronaut lies along the motion of the rocket, so his height will be Lorentz-contracted.

SET UP: The doctor in the rocket measures his proper length l_0.

EXECUTE: **(a)** $l_0 = 2.00\text{ m}$. $l = l_0\sqrt{1-u^2/c^2} = (2.00\text{ m})\sqrt{1-(0.910)^2} = 0.829\text{ m}$. The person on earth would measure his height to be 0.829 m.

(b) $l = 2.00\text{ m}$. $l_0 = \dfrac{l}{\sqrt{1-u^2/c^2}} = \dfrac{2.00\text{ m}}{\sqrt{1-(0.910)^2}} = 4.82\text{ m}$. This is not a reasonable height for a human.

(c) There is no length contraction in a direction perpendicular to the motion and both observers measure the same height, 2.00 m.

EVALUATE: The length of an object moving with respect to the observer is shortened in the direction of the motion, so in (a) and (b) the observer on earth measures a shorter height.

37.15. **IDENTIFY:** Apply $v_x = \dfrac{v'_x + u}{1 + uv'_x/c^2}$.

SET UP: The velocities $\vec{v}'$ and $\vec{v}$ are both in the $+x$-direction, so $v'_x = v'$ and $v_x = v$.

EXECUTE: **(a)** $v = \dfrac{v'+u}{1+uv'/c^2} = \dfrac{0.400c + 0.600c}{1+(0.400)(0.600)} = 0.806c$.

(b) $v = \dfrac{v'+u}{1+uv'/c^2} = \dfrac{0.900c + 0.600c}{1+(0.900)(0.600)} = 0.974c$.

(c) $v = \dfrac{v'+u}{1+uv'/c^2} = \dfrac{0.990c + 0.600c}{1+(0.990)(0.600)} = 0.997c$.

EVALUATE: Speed v is always less than c, even when $v'+u$ is greater than c.

37.16. **IDENTIFY:** Apply $\Delta t = \gamma \Delta t_0$ and the equations for x and t that are developed in Example 37.6.

SET UP: S is Stanley's frame and S' is Mavis's frame. The proper time for the two events is the time interval measured in Mavis's frame. $\gamma = 1.667$ ($\gamma = 5/3$ if $u = (4/5)$c).

EXECUTE: **(a)** In Mavis's frame the event "light on" has space-time coordinates $x' = 0$ and $t' = 5.00\text{ s}$, so from the result of Example 37.6, $x = \gamma(x' + ut')$ and

$t = \gamma\left(t' + \dfrac{ux'}{c^2}\right) \Rightarrow x = \gamma ut' = 2.00\times10^9\text{ m}, t = \gamma t' = 8.33\text{ s}.$

(b) The 5.00-s interval in Mavis's frame is the proper time Δt_0, so $\Delta t = \gamma\Delta t_0 = 8.33\text{ s}$, the same as in part (a).

(c) $(8.33\text{ s})(0.800c) = 2.00\times10^9\text{ m}$, which is the distance x found in part (a).

EVALUATE: Mavis would measure that she would be a distance $(5.00\text{ s})(0.800c) = 1.20\times10^9\text{ m}$ from Stanley when she turns on her light. In $l = l_0/\gamma$, $l_0 = 2.00\times10^9\text{ m}$ and $l = 1.20\times10^9\text{ m}$.

37.17. **IDENTIFY:** The relativistic velocity addition formulas apply since the speeds are close to that of light.

SET UP: The relativistic velocity addition formula is $v'_x = \dfrac{v_x - u}{1 - \dfrac{uv_x}{c^2}}$.

EXECUTE: **(a)** For the pursuit ship to catch the cruiser, the distance between them must be decreasing, so the velocity of the cruiser relative to the pursuit ship must be directed toward the pursuit ship.

(b) Let the unprimed frame be Tatooine and let the primed frame be the pursuit ship. We want the velocity v' of the cruiser knowing the velocity of the primed frame u and the velocity of the cruiser v in the unprimed frame (Tatooine).

$$v'_x = \frac{v_x - u}{1 - \dfrac{uv_x}{c^2}} = \frac{0.600c - 0.800c}{1-(0.600)(0.800)} = -0.385c.$$

The result implies that the cruiser is moving toward the pursuit ship at $0.385c$.

EVALUATE: The nonrelativistic formula would have given $-0.200c$, which is considerably different from the correct result.

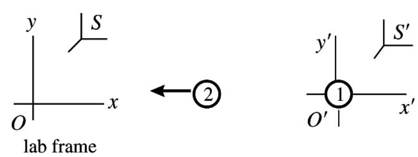
37.18. **IDENTIFY** and **SET UP:** Let the starfighter's frame be S and let the enemy spaceship's frame be S'. Let the positive x-direction for both frames be from the enemy spaceship toward the starfighter. Then $u = +0.400c$. $v' = +0.700c$. v is the velocity of the missile relative to you.

EXECUTE: **(a)** $v = \dfrac{v' + u}{1 + uv'/c^2} = \dfrac{0.700c + 0.400c}{1 + (0.400)(0.700)} = 0.859c.$

(b) Use the distance it moves as measured in your frame and the speed it has in your frame to calculate the time it takes in your frame. $t = \dfrac{8.00\times 10^9\ \text{m}}{(0.859)(3.00\times 10^8\ \text{m/s})} = 31.0\ \text{s}.$

EVALUATE: Note that the speed in (a) is not $1.1c$ as nonrelativistic physics would predict.

37.19. **IDENTIFY** and **SET UP:** Reference frames S and S' are shown in Figure 37.19.



Frame S is at rest in the laboratory. Frame S' is attached to particle 1.

Figure 37.19

u is the speed of S' relative to S; this is the speed of particle 1 as measured in the laboratory. Thus $u = +0.650c$. The speed of particle 2 in S' is $0.950c$. Also, since the two particles move in opposite directions, 2 moves in the $-x'$-direction and $v'_x = -0.950c$. We want to calculate v_x, the speed of particle 2 in frame S, so use $v_x = \dfrac{v'_x + u}{1 + uv'_x/c^2}$.

EXECUTE: $v_x = \dfrac{v'_x + u}{1 + uv'_x/c^2} = \dfrac{-0.950c + 0.650c}{1 + (0.650c)(-0.950c)/c^2} = \dfrac{-0.300c}{1 - 0.6175} = -0.784c.$ The speed of the second particle, as measured in the laboratory, is $0.784c$.

EVALUATE: The incorrect Galilean expression for the relative velocity gives that the speed of the second particle in the lab frame is $0.300c$. The correct relativistic calculation gives a result more than twice this.

37.20. **IDENTIFY** and **SET UP:** Let S be the laboratory frame and let S' be the frame of one of the particles, as shown in Figure 37.20. Let the positive x-direction for both frames be from particle 1 to particle 2. In the lab frame particle 1 is moving in the $+x$-direction and particle 2 is moving in the $-x$-direction. Then $u = 0.9380c$ and $v_x = -0.9380c$. v'_x is the velocity of particle 2 relative to particle 1.

EXECUTE: $v'_x = \dfrac{v_x - u}{1 - uv_x/c^2} = \dfrac{-0.9380c - 0.9380c}{1 - (0.9380c)(-0.9380c)/c^2} = -0.9980c.$ The speed of particle 2 relative to particle 1 is $0.9980c$.

EVALUATE: $v'_x < 0$ shows particle 2 is moving toward particle 1.

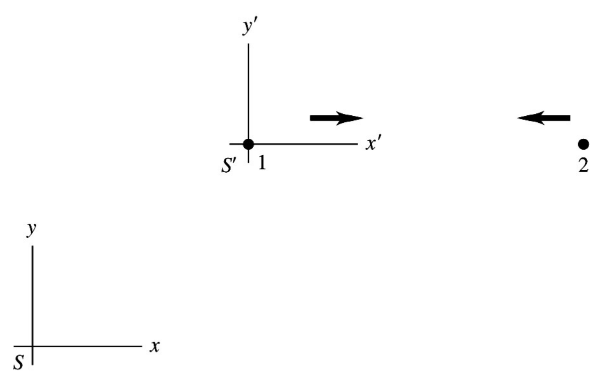


Figure 37.20

37.21. IDENTIFY: The relativistic velocity addition formulas apply since the speeds are close to that of light.

SET UP: The relativistic velocity addition formula is $v'_x = \dfrac{v_x - u}{1 - \dfrac{uv_x}{c^2}}$.

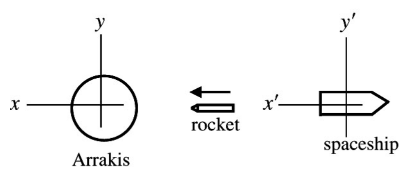
EXECUTE: In the relativistic velocity addition formula for this case, v'_x is the relative speed of particle 1 with respect to particle 2, v is the speed of particle 2 measured in the laboratory, and u is the speed of particle 1 measured in the laboratory, $u = -v$.

$v'_x = \dfrac{v-(-v)}{1-(-v)v/c^2} = \dfrac{2v}{1+v^2/c^2}$. $\dfrac{v'_x}{c^2}v^2 - 2v + v'_x = 0$ and $(0.890c)v^2 - 2c^2 v + (0.890c^3) = 0$.

This is a quadratic equation with solution $v = 0.611c$ (v must be less than c).

EVALUATE: The nonrelativistic result would be $0.445c$, which is considerably different from this result.

37.22. IDENTIFY and SET UP: The reference frames are shown in Figure 37.22.



S = Arrakis frame.
S' = spaceship frame.
The object is the rocket.

Figure 37.22

u is the velocity of the spaceship relative to Arrakis.
$v_x = +0.360c$; $v'_x = +0.920c$.
(In each frame the rocket is moving in the positive coordinate direction.)

Use the Lorentz velocity transformation equation $v'_x = \dfrac{v_x - u}{1 - uv_x/c^2}$.

EXECUTE: $v'_x = \dfrac{v_x - u}{1-uv_x/c^2}$ so $v'_x - u\left(\dfrac{v_x v'_x}{c^2}\right) = v_x - u$ and $u\left(1 - \dfrac{v_x v'_x}{c^2}\right) = v_x - v'_x$.

$$u = \frac{v_x - v'_x}{1 - v_x v'_x/c^2} = \frac{0.360c - 0.920c}{1-(0.360c)(0.920c)/c^2} = -\frac{0.560c}{0.6688} = -0.837c.$$

The speed of the spacecraft relative to Arrakis is $0.837c = 2.51\times10^8$ m/s. The minus sign in our result for u means that the spacecraft is moving in the $-x$-direction, so it is moving away from Arrakis.

EVALUATE: The incorrect Galilean expression also says that the spacecraft is moving away from Arrakis, but with speed $0.920c - 0.360c = 0.560c$.

37.23. IDENTIFY and SET UP: Source and observer are approaching, so use $f = \sqrt{\dfrac{c+u}{c-u}}f_0$. Solve for u, the speed of the light source relative to the observer.

EXECUTE: **(a)** $f^2 = \left(\dfrac{c+u}{c-u}\right)f_0^2$.

$(c-u)f^2 = (c+u)f_0^2$ and $u = \dfrac{c(f^2 - f_0^2)}{f^2 + f_0^2} = c\left(\dfrac{(f/f_0)^2 - 1}{(f/f_0)^2 + 1}\right)$.

$\lambda_0 = 675$ nm, $\lambda = 575$ nm.

$u = \left(\dfrac{(675\text{ nm}/575\text{ nm})^2 - 1}{(675\text{ nm}/575\text{ nm})^2 + 1}\right)c = 0.159c = (0.159)(2.998\times10^8\text{ m/s}) = 4.77\times10^7$ m/s; definitely speeding

(b) $4.77\times10^7\text{ m/s} = (4.77\times10^7\text{ m/s})(1\text{ km}/1000\text{ m})(3600\text{ s}/1\text{ h}) = 1.72\times10^8$ km/h. Your fine would be $\$1.72\times10^8$ (172 million dollars).

EVALUATE: The source and observer are approaching, so $f > f_0$ and $\lambda < \lambda_0$. Our result gives $u < c$, as it must.

37.24. IDENTIFY: There is a Doppler effect in the frequency of the radiation due to the motion of the star.

SET UP: The star is moving away from the earth, so $f = \sqrt{\dfrac{c-u}{c+u}} f_0$.

EXECUTE: $f = \sqrt{\dfrac{c-0.520c}{c+0.520c}} f_0 = 0.5620 f_0 = (0.5620)(8.64\times10^{14}\text{ Hz}) = 4.86\times10^{14}\text{ Hz}.$

EVALUATE: The earth observer measures a lower frequency than the star emits because the star is moving away from the earth.

37.25. IDENTIFY: There is a Doppler effect in the frequency of the radiation due to the motion of the source.

SET UP: $f > f_0$ so the source is moving toward you. $f = \sqrt{\dfrac{c-u}{c+u}} f_0$.

EXECUTE: $(f/f_0)^2 = \dfrac{c+u}{c-u}$. $c(f/f_0)^2 - (f/f_0)^2 u = c + u$.

$$u = \frac{c[(f/f_0)^2 - 1]}{(f/f_0)^2 + 1} = \left[\frac{(1.25)^2 - 1}{(1.25)^2 + 1}\right] c = 0.220c, \text{ toward you.}$$

EVALUATE: The difference in frequency is rather large (1.25 times), so the motion of the source must be a substantial fraction of the speed of light (around 20% in this case).

37.26. IDENTIFY and **SET UP:** The force is found from $F = \gamma^3 ma$ or $F = \gamma ma$, whichever is applicable.

EXECUTE: **(a)** Indistinguishable from $F = ma = 0.145\text{ N}$.

(b) $\gamma^3 ma = 1.75\text{ N}$.

(c) $\gamma^3 ma = 51.7\text{ N}$.

(d) $\gamma ma = 0.145\text{ N},\ 0.333\text{ N}, 1.03\text{ N}$.

EVALUATE: When v is large, much more force is required to produce a given magnitude of acceleration when the force is parallel to the velocity than when the force is perpendicular to the velocity.

37.27. IDENTIFY: The speed of the proton is a substantial fraction of the speed of light, so we must use the relativistic formula for momentum.

SET UP: $p = \gamma mv$. $p_0 = \gamma_0 m v_0$. $\dfrac{p}{p_0} = \dfrac{\gamma v}{\gamma_0 v_0}$. $v/v_0 = 2.00$.

EXECUTE: $\gamma_0 = \dfrac{1}{\sqrt{1 - v_0^2/c^2}} = \dfrac{1}{\sqrt{1-(0.400)^2}} = 1.0911.$ $\gamma = \dfrac{1}{\sqrt{1-(0.800)^2}} = 1.667.$

$$p = p_0(2)\left(\frac{1.667}{1.091}\right) = 3.06 p_0.$$

EVALUATE: The speed doubles but the momentum more than triples.

37.28. IDENTIFY and **SET UP:** $\gamma = \dfrac{1}{\sqrt{1 - v^2/c^2}}$. If γ is 1.0% greater than 1 then $\gamma = 1.010$, if γ is 10% greater than 1 then $\gamma = 1.10$ and if γ is 100% greater than 1 then $\gamma = 2.00$.

EXECUTE: $v = c\sqrt{1 - 1/\gamma^2}$.

(a) $v = c\sqrt{1 - 1/(1.010)^2} = 0.140c$.

(b) $v = c\sqrt{1 - 1/(1.10)^2} = 0.417c$.

(c) $v = c\sqrt{1 - 1/(2.00)^2} = 0.866c$.

EVALUATE: From these results, we see that relativistic results start to become important when $v \approx 0.1c$.

37.29. **IDENTIFY:** Apply $p=\dfrac{mv}{\sqrt{1-v^2/c^2}}$ and $F=\gamma^3 ma.$

SET UP: For a particle at rest (or with $v \ll c$), $a=F/m.$

EXECUTE: **(a)** $p=\dfrac{mv}{\sqrt{1-v^2/c^2}}=2mv.$

$\Rightarrow 1=2\sqrt{1-v^2/c^2} \Rightarrow \tfrac{1}{4}=1-\dfrac{v^2}{c^2} \Rightarrow v^2=\tfrac{3}{4}c^2 \Rightarrow v=\dfrac{\sqrt{3}}{2}c=0.866c.$

(b) $F=\gamma^3 ma=2ma \Rightarrow \gamma^3=2 \Rightarrow \gamma=(2)^{1/3}$ so $\dfrac{1}{1-v^2/c^2}=2^{2/3} \Rightarrow \dfrac{v}{c}=\sqrt{1-2^{-2/3}}=0.608.$

EVALUATE: The momentum of a particle and the force required to give it a given acceleration both increase without bound as the speed of the particle approaches c.

37.30. **IDENTIFY:** When the speed of the electron is close to the speed of light, we must use the relativistic form of Newton's second law.

SET UP: When the force and velocity are parallel, as in part (b), $F=\dfrac{ma}{(1-v^2/c^2)^{3/2}}$. In part (a), $v \ll c$ so $F=ma.$

EXECUTE: **(a)** $a=\dfrac{F}{m}=\dfrac{5.00\times10^{-15}\text{ N}}{9.11\times10^{-31}\text{ kg}}=5.49\times10^{15}\text{ m/s}^2.$

(b) $\gamma=\dfrac{1}{(1-v^2/c^2)^{1/2}}=\dfrac{1}{(1-[2.50\times10^8/3.00\times10^8]^2)^{1/2}}=1.81.$

$a=\dfrac{F}{m\gamma^3}=\dfrac{5.49\times10^{15}\text{ m/s}^2}{(1.81)^3}=9.26\times10^{14}\text{ m/s}^2.$

EVALUATE: The acceleration for low speeds is over 5 times greater than it is near the speed of light as in (b).

37.31. **IDENTIFY:** Apply $K=\dfrac{mc^2}{\sqrt{1-v^2/c^2}}-mc^2.$

SET UP: The rest energy is mc^2.

EXECUTE: **(a)** $K=\dfrac{mc^2}{\sqrt{1-v^2/c^2}}-mc^2=mc^2$

$$\Rightarrow \frac{1}{\sqrt{1-v^2/c^2}}=2 \Rightarrow \frac{1}{4}=1-\frac{v^2}{c^2} \Rightarrow v=\sqrt{\frac{3}{4}}c=0.866c.$$

(b) $K=5mc^2 \Rightarrow \dfrac{1}{\sqrt{1-v^2/c^2}}=6 \Rightarrow \dfrac{1}{36}=1-\dfrac{v^2}{c^2} \Rightarrow v=\sqrt{\dfrac{35}{36}}c=0.986c.$

EVALUATE: If $v \ll c$, then K is much less than the rest energy of the particle.

37.32. **IDENTIFY:** At such a high speed, we must use the relativistic formulas for momentum and kinetic energy.

SET UP: $m_\mu=207m_\mathrm{e}=1.89\times10^{-28}$ kg. v is very close to c and we must use relativistic expressions.

$p=\dfrac{mv}{\sqrt{1-v^2/c^2}}$, $K=\dfrac{mc^2}{\sqrt{1-v^2/c^2}}-mc^2.$

EXECUTE: $p=\dfrac{mv}{\sqrt{1-v^2/c^2}}=\dfrac{(1.89\times10^{-28}\text{ kg})(0.999)(3.00\times10^8\text{ m/s})}{\sqrt{1-(0.999)^2}}=1.27\times10^{-18}\text{ kg}\cdot\text{m/s}.$

Using $K=\dfrac{mc^2}{\sqrt{1-v^2/c^2}}-mc^2$ gives

$$K = (1.89\times10^{-28}\text{ kg})(3.00\times10^{8}\text{ m/s})^2\left(\frac{1}{\sqrt{1-(0.999)^2}}-1\right) = 3.63\times10^{-10}\text{ J}.$$

EVALUATE: The nonrelativistic values are $p_{\text{nr}} = mv = 5.66\times10^{-20}\text{ kg}\cdot\text{m/s}$ and $K_{\text{nr}} = \frac{1}{2}mv^2 = 8.49\times10^{-12}\text{ J}$. Each relativistic result is much larger.

37.33. IDENTIFY and SET UP: Use $E = mc^2 + K$ and $E^2 = (mc^2)^2 + (pc)^2$.

EXECUTE: **(a)** $E = mc^2 + K$, so $E = 4.00mc^2$ means $K = 3.00mc^2 = 4.50\times10^{-10}\text{ J}$.

(b) $E^2 = (mc^2)^2 + (pc)^2$; $E = 4.00mc^2$, so $15.0(mc^2)^2 = (pc)^2$.

$p = \sqrt{15}mc = 1.94\times10^{-18}\text{ kg}\cdot\text{m/s}$.

(c) $E = mc^2/\sqrt{1-v^2/c^2}$.

$E = 4.00mc^2$ gives $1 - v^2/c^2 = 1/16$ and $v = \sqrt{15/16}c = 0.968c$.

EVALUATE: The speed is close to c since the kinetic energy is greater than the rest energy. Nonrelativistic expressions relating E, K, p, and v will be very inaccurate.

37.34. IDENTIFY: Apply the work energy theorem in the form $W = \Delta K$.

SET UP: K is given by $K = (\gamma - 1)mc^2$. When $v = 0$, $\gamma = 1$.

EXECUTE: **(a)** $W = \Delta K = (\gamma_{\text{f}} - 1)mc^2 = (4.07\times10^{-3})\,mc^2$.

(b) $(\gamma_{\text{f}} - \gamma_{\text{i}})\,mc^2 = 4.79mc^2$.

(c) The result of part (b) is far larger than that of part (a).

EVALUATE: The amount of work required to produce a given increase in speed (in this case an increase of $0.090c$) increases as the initial speed increases.

37.35. IDENTIFY and SET UP: The energy equivalent of mass is $E = mc^2$. $\rho = 7.86\text{ g/cm}^3 = 7.86\times10^3\text{ kg/m}^3$. For a cube, $V = L^3$.

EXECUTE: **(a)** $m = \dfrac{E}{c^2} = \dfrac{1.0\times10^{20}\text{ J}}{(3.00\times10^8\text{ m/s})^2} = 1.11\times10^3\text{ kg}$.

(b) $\rho = \dfrac{m}{V}$ so $V = \dfrac{m}{\rho} = \dfrac{1.11\times10^3\text{ kg}}{7.86\times10^3\text{ kg/m}^3} = 0.141\text{ m}^3$. $L = V^{1/3} = 0.521\text{ m} = 52.1\text{ cm}$.

EVALUATE: Particle/antiparticle annihilation has been observed in the laboratory, but only with small quantities of antimatter.

37.36. IDENTIFY: With such a large potential difference, the electrons will be accelerated to relativistic speeds, so we must use the relativistic formula for kinetic energy.

SET UP: $K = \left(\dfrac{1}{\sqrt{1-v^2/c^2}} - 1\right)mc^2$. The classical expression for kinetic energy is $K = \frac{1}{2}mv^2$.

EXECUTE: For an electron $mc^2 = (9.11\times10^{-31}\text{ kg})(3.00\times10^8\text{ m/s})^2 = 8.20\times10^{-14}\text{ J}$.

$K = 7.50\times10^5\text{ eV} = 1.20\times10^{-13}\text{ J}$.

(a) $\dfrac{K}{mc^2} + 1 = \dfrac{1}{\sqrt{1-v^2/c^2}}$. $\dfrac{1}{\sqrt{1-v^2/c^2}} = \dfrac{1.20\times10^{-13}\text{ J}}{8.20\times10^{-14}\text{ J}} + 1 = 2.46$.

$v = c\sqrt{1-(1/2.46)^2} = 0.914c = 2.74\times10^8\text{ m/s}$.

(b) $K = \frac{1}{2}mv^2$ gives $v = \sqrt{\dfrac{2K}{m}} = \sqrt{\dfrac{2(1.20\times10^{-13}\text{ J})}{9.11\times10^{-31}\text{ kg}}} = 5.13\times10^8\text{ m/s}$.

EVALUATE: At a given speed the relativistic value of the kinetic energy is larger than the nonrelativistic value. Therefore, for a given kinetic energy the relativistic expression for kinetic energy gives a smaller speed than the nonrelativistic expression.

37.37. **IDENTIFY** and **SET UP:** The total energy is given in terms of the momentum by $E^2 = (mc^2)^2 + (pc)^2$. In terms of the total energy E, the kinetic energy K is $K = E - mc^2$. The rest energy is mc^2.

EXECUTE: **(a)** $E = \sqrt{(mc^2)^2 + (pc)^2} = \sqrt{\left[(6.64\times10^{-27})(2.998\times10^8)^2\right]^2 + \left[(2.10\times10^{-18})(2.998\times10^8)\right]^2}$ J.

$E = 8.67\times10^{-10}$ J.

(b) $mc^2 = (6.64\times10^{-27}\text{ kg})(2.998\times10^8\text{ m/s})^2 = 5.97\times10^{-10}$ J.

$K = E - mc^2 = 8.67\times10^{-10}\text{ J} - 5.97\times10^{-10}\text{ J} = 2.70\times10^{-10}$ J.

(c) $\dfrac{K}{mc^2} = \dfrac{2.70\times10^{-10}\text{ J}}{5.97\times10^{-10}\text{ J}} = 0.452.$

EVALUATE: The incorrect nonrelativistic expressions for K and p give $K = p^2/2m = 3.3\times10^{-10}$ J; the correct relativistic value is less than this.

37.38. **IDENTIFY:** The total energy is conserved in the collision.

SET UP: Use $E = mc^2 + K$ for the total energy. Since all three particles are at rest after the collision, the final total energy is $2Mc^2 + mc^2$. The initial total energy of the two protons is $\gamma 2Mc^2$.

EXECUTE: **(a)** $2Mc^2 + mc^2 = \gamma 2Mc^2 \Rightarrow \gamma = 1 + \dfrac{m}{2M} = 1 + \dfrac{9.75}{2(16.7)} = 1.292.$

Note that since $\gamma = \dfrac{1}{\sqrt{1 - v^2/c^2}}$, we have that $\dfrac{v}{c} = \sqrt{1 - \dfrac{1}{\gamma^2}} = \sqrt{1 - \dfrac{1}{(1.292)^2}} = 0.6331.$

(b) According to $K = (\gamma - 1)mc^2$ the kinetic energy of each proton is

$K = (\gamma - 1)Mc^2 = (1.292 - 1)(1.67\times10^{-27}\text{ kg})(3.00\times10^8\text{ m/s})^2\left(\dfrac{1.00\text{ MeV}}{1.60\times10^{-13}\text{ J}}\right) = 274\text{ MeV}.$

(c) The rest energy of η^0 is $mc^2 = (9.75\times10^{-28}\text{ kg})(3.00\times10^8\text{ m/s})^2\left(\dfrac{1.00\text{ MeV}}{1.60\times10^{-13}\text{ J}}\right) = 548\text{ MeV}.$

EVALUATE: **(d)** The kinetic energy lost by the protons is the energy that produces the η^0, $548\text{ MeV} = 2(274\text{ MeV})$.

37.39. **IDENTIFY** and **SET UP:** The nonrelativistic expression is $K_{\text{nonrel}} = \frac{1}{2}mv^2$ and the relativistic expression is $K_{\text{rel}} = (\gamma - 1)mc^2$.

EXECUTE: **(a)** $v = 8\times10^7\text{ m/s} \Rightarrow \gamma = \dfrac{1}{\sqrt{1 - v^2/c^2}} = 1.0376$. For $m = m_{\text{p}}$, $K_{\text{nonrel}} = \frac{1}{2}mv^2 = 5.34\times10^{-12}$ J.

$K_{\text{rel}} = (\gamma - 1)mc^2 = 5.65\times10^{-12}$ J. $\dfrac{K_{\text{rel}}}{K_{\text{nonrel}}} = 1.06.$

(b) $v = 2.85\times10^8$ m/s; $\gamma = 3.203$.

$K_{\text{nonrel}} = \dfrac{1}{2}mv^2 = 6.78\times10^{-11}$ J; $K_{\text{rel}} = (\gamma - 1)mc^2 = 3.31\times10^{-10}$ J; $K_{\text{rel}}/K_{\text{nonrel}} = 4.88$.

EVALUATE: $K_{\text{rel}}/K_{\text{nonrel}}$ increases without bound as v approaches c.

37.40. **IDENTIFY:** Since the speeds involved are close to that of light, we must use the relativistic formula for kinetic energy.

SET UP: The relativistic kinetic energy is $K = (\gamma - 1)mc^2 = \left(\dfrac{1}{\sqrt{1 - v^2/c^2}} - 1\right)mc^2.$

EXECUTE: (a)

$$K=(\gamma-1)mc^2=\left(\frac{1}{\sqrt{1-v^2/c^2}}-1\right)mc^2=(1.67\times10^{-27}\text{ kg})(3.00\times10^8\text{ m/s})^2\left(\frac{1}{\sqrt{1-(0.100c/c)^2}}-1\right).$$

$$K=(1.50\times10^{-10}\text{ J})\left(\frac{1}{\sqrt{1-0.0100}}-1\right)=7.56\times10^{-13}\text{ J}=4.73\text{ MeV}.$$

(b) $K=(1.50\times10^{-10}\text{J})\left(\frac{1}{\sqrt{1-(0.500)^2}}-1\right)=2.32\times10^{-11}\text{ J}=145\text{ MeV}.$

(c) $K=(1.50\times10^{-10}\text{ J})\left(\frac{1}{\sqrt{1-(0.900)^2}}-1\right)=1.94\times10^{-10}\text{ J}=1210\text{ MeV}.$

(d) $\Delta E=2.32\times10^{-11}\text{ J}-7.56\times10^{-13}\text{ J}=2.24\times10^{-11}\text{ J}=140\text{ MeV}.$

(e) $\Delta E=1.94\times10^{-10}\text{ J}-2.32\times10^{-11}\text{ J}=1.71\times10^{-10}\text{ J}=1070\text{ MeV}.$

(f) Without relativity, $K=\frac{1}{2}mv^2$. The work done in accelerating a proton from $0.100c$ to $0.500c$ in the nonrelativistic limit is $\Delta E=\frac{1}{2}m(0.500c)^2-\frac{1}{2}m(0.100c)^2=1.81\times10^{-11}\text{ J}=113\text{ MeV}.$

The work done in accelerating a proton from $0.500c$ to $0.900c$ in the nonrelativistic limit is

$$\Delta E=\tfrac{1}{2}m(0.900c)^2-\tfrac{1}{2}m(0.500c)^2=4.21\times10^{-11}\text{ J}=263\text{ MeV}.$$

EVALUATE: We see in the first case the nonrelativistic result is within 20% of the relativistic result. In the second case, the nonrelativistic result is very different from the relativistic result since the velocities are closer to c.

37.41. IDENTIFY and SET UP: Use $K=q\Delta V=e\Delta V$ and conservation of energy to relate the potential difference to the kinetic energy gained by the electron. Use $K=mc^2\left(\frac{1}{\sqrt{1-v^2/c^2}}-1\right)$ to calculate the kinetic energy from the speed.

EXECUTE: (a) $K=q\Delta V=e\Delta V$.

$$K=mc^2\left(\frac{1}{\sqrt{1-v^2/c^2}}-1\right)=4.025mc^2=3.295\times10^{-13}\text{ J}=2.06\text{ MeV}.$$

$\Delta V=K/e=2.06\times10^6\text{ V}.$

(b) From part (a), $K=3.30\times10^{-13}\text{ J}=2.06\text{ MeV}.$

EVALUATE: The speed is close to c and the kinetic energy is four times the rest mass.

37.42. IDENTIFY: Use $E=mc^2$ to relate the mass decrease to the energy produced.

SET UP: 1 kg is equivalent to 2.2 lbs and 1 ton = 2000 lbs. 1 W = 1 J/s.

EXECUTE: (a) $E=mc^2,\ m=E/c^2=(3.8\times10^{26}\text{ J})/(2.998\times10^8\text{ m/s})^2=4.2\times10^9\text{ kg}=4.6\times10^6\text{ tons}.$

(b) The current mass of the sun is 1.99×10^{30} kg, so it would take it $(1.99\times10^{30}\text{ kg})/(4.2\times10^9\text{ kg/s})=4.7\times10^{20}\text{s}=1.5\times10^{13}$ years to use up all its mass.

EVALUATE: The power output of the sun is very large, but only a small fraction of the sun's mass is converted to energy each second.

37.43. (a) IDENTIFY and SET UP: $\Delta t_0=2.60\times10^{-8}$ s is the proper time, measured in the pion's frame. The time measured in the lab must satisfy $d=c\Delta t$, where $u\approx c$. Calculate Δt and then use Eq. (37.6) to calculate u.

EXECUTE: $\Delta t = \dfrac{d}{c} = \dfrac{1.90\times10^3\text{ m}}{2.998\times10^8\text{ m/s}} = 6.3376\times10^{-6}\text{ s}$. $\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}}$ so $(1-u^2/c^2)^{1/2} = \dfrac{\Delta t_0}{\Delta t}$ and

$(1-u^2/c^2) = \left(\dfrac{\Delta t_0}{\Delta t}\right)^2$. Write $u=(1-\Delta)c$ so that $(u/c)^2 = (1-\Delta)^2 = 1-2\Delta+\Delta^2 \approx 1-2\Delta$ since Δ is small.

Using this in the above gives $1-(1-2\Delta) = \left(\dfrac{\Delta t_0}{\Delta t}\right)^2$. $\Delta = \frac{1}{2}\left(\dfrac{\Delta t_0}{\Delta t}\right)^2 = \frac{1}{2}\left(\dfrac{2.60\times10^{-8}\text{ s}}{6.3376\times10^{-6}\text{ s}}\right)^2 = 8.42\times10^{-6}$.

EVALUATE: An alternative calculation is to say that the length of the tube must contract relative to the moving pion so that the pion travels that length before decaying. The contracted length must be

$l = c\Delta t_0 = (2.998\times10^8\text{ m/s})(2.60\times10^{-8}\text{ s}) = 7.7948\text{ m}$. $l = l_0\sqrt{1-u^2/c^2}$ so $1-u^2/c^2 = \left(\dfrac{l}{l_0}\right)^2$. Then

$u=(1-\Delta)c$ gives $\Delta = \frac{1}{2}\left(\dfrac{l}{l_0}\right)^2 = \frac{1}{2}\left(\dfrac{7.7948\text{ m}}{1.90\times10^3\text{ m}}\right)^2 = 8.42\times10^{-6}$, which checks.

(b) IDENTIFY and **SET UP:** $E = \gamma mc^2$ Eq. (37.38).

EXECUTE: $\gamma = \dfrac{1}{\sqrt{1-u^2/c^2}} = \dfrac{1}{\sqrt{2\Delta}} = \dfrac{1}{\sqrt{2(8.42\times10^{-6})}} = 244.$

$E = (244)(139.6\text{ MeV}) = 3.40\times10^4\text{ MeV} = 34.0\text{ GeV}.$

EVALUATE: The total energy is 244 times the rest energy.

37.44. **IDENTIFY** and **SET UP:** The astronaut in the spaceship measures the proper time, since the end of a swing occurs at the same location in his frame. $\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}}$.

EXECUTE: **(a)** $\Delta t_0 = 1.80\text{ s}$. $\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}} = \dfrac{1.80\text{ s}}{\sqrt{1-(0.75c/c)^2}} = 2.72\text{ s}.$

(b) $\Delta t = 1.80\text{ s}$. $\Delta t_0 = \Delta t\sqrt{1-u^2/c^2} = (1.80\text{ s})\sqrt{1-(0.75c/c)^2} = 1.19\text{ s}.$

EVALUATE: The motion of the spaceship makes a considerable difference in the measured values for the period of the pendulum!

37.45. **IDENTIFY** and **SET UP:** There must be a length contraction such that the length a becomes the same as b; $l_0 = a$, $l = b$. l_0 is the distance measured by an observer at rest relative to the spacecraft. Use $l = l_0\sqrt{1-u^2/c^2}$ and solve for u.

EXECUTE: $\dfrac{l}{l_0} = \sqrt{1-u^2/c^2}$ so $\dfrac{b}{a} = \sqrt{1-u^2/c^2}$;

$a = 1.40b$ gives $b/1.40b = \sqrt{1-u^2/c^2}$. and thus $1-u^2/c^2 = 1/(1.40)^2$.

$u = \sqrt{1-1/(1.40)^2}\,c = 0.700c = 2.10\times10^8\text{ m/s}.$

EVALUATE: A length on the spacecraft in the direction of the motion is shortened. A length perpendicular to the motion is unchanged.

37.46. **IDENTIFY** and **SET UP:** The proper length of a side is $l_0 = a$. The side along the direction of motion is shortened to $l = l_0\sqrt{1-v^2/c^2}$. The sides in the two directions perpendicular to the motion are unaffected by the motion and still have a length a.

EXECUTE: $V = a^2 l = a^3\sqrt{1-v^2/c^2}$.

EVALUATE: Only the side parallel to the direction of motion is contracted.

37.47. **IDENTIFY** and **SET UP:** The proper time Δt_0 is the time that elapses in the frame of the space probe. Δt is the time that elapses in the frame of the earth. The distance traveled is 42.2 light years, as measured in the earth frame.

EXECUTE: Light travels 42.2 light years in 42.2 y, so $\Delta t = \left(\dfrac{c}{0.9930c}\right)(42.2 \text{ y}) = 42.5 \text{ y}.$

$\Delta t_0 = \Delta t\sqrt{1-u^2/c^2} = (42.5 \text{ y})\sqrt{1-(0.9930)^2} = 5.0 \text{ y}.$ She measures her biological age to be $19 \text{ y} + 5.0 \text{ y} = 24.0 \text{ y}.$

EVALUATE: Her age measured by someone on earth is $19 \text{ y} + 42.5 \text{ y} = 61.5 \text{ y}.$

37.48. IDENTIFY: The height measured in the earth's frame is a proper length. The lifetime measured in the muon's frame is the proper time.

SET UP: Use $l = l_0\sqrt{1-u^2/c^2}$ and $\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}}.$

EXECUTE: **(a)** $l_0 = 55.0$ km. $l = l_0\sqrt{1-u^2/c^2} = (55.0 \text{ km})\sqrt{1-(0.9860)^2} = 9.17 \text{ km}.$

(b) In the muon's frame its lifetime is $2.20\ \mu\text{s},$ so the distance it travels during its lifetime is

$(2.20\times 10^{-6} \text{ s})(0.9860)(3.00\times 10^8 \text{ m/s}) = 651 \text{ m}.$ This is $\dfrac{651 \text{ m}}{9.17\times 10^3 \text{ m}} = 7.1\%$ of its initial height.

(c) $\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}} = \dfrac{2.20\times 10^{-6} \text{ s}}{\sqrt{1-(0.9860)^2}} = 1.32\times 10^{-5} \text{ s}.$ The distance it travels in the earth's frame during this time is $(1.32\times 10^{-5} \text{ s})(0.9860)(3.00\times 10^8 \text{ m/s}) = 3.90 \text{ km}.$ This is $\dfrac{3.90 \text{ km}}{55.0 \text{ km}} = 7.1\%$ of its initial height measured in the earth's frame.

EVALUATE: There are two equivalent views. In the muon's frame, its distance above the surface of the earth is contracted because the earth is moving relative to the muon. In the earth's frame the lifetime of the muon is dilated due to the motion of the muon relative to the earth.

37.49. IDENTIFY: Since the speed is very close to the speed of light, we must use the relativistic formula for kinetic energy.

SET UP: The relativistic formula for kinetic energy is $K = mc^2\left(\dfrac{1}{\sqrt{1-v^2/c^2}} - 1\right)$ and the relativistic mass is $m_{\text{rel}} = \dfrac{m}{\sqrt{1-v^2/c^2}}.$

EXECUTE: **(a)** $K = 7.0\times 10^{12} \text{ eV} = 1.12\times 10^{-6} \text{ J}.$ Using this value in the relativistic kinetic energy formula and substituting the mass of the proton for *m*, we get $K = mc^2\left(\dfrac{1}{\sqrt{1-v^2/c^2}} - 1\right)$ which gives

$\dfrac{1}{\sqrt{1-v^2/c^2}} = 7.45\times 10^3$ and $1-\dfrac{v^2}{c^2} = \dfrac{1}{(7.45\times 10^3)^2}.$ Solving for *v* gives $1-\dfrac{v^2}{c^2} = \dfrac{(c+v)(c-v)}{c^2} = \dfrac{2(c-v)}{c},$

since $c+v \approx 2c.$ Substituting $v = (1-\Delta)c,$ we have $1-\dfrac{v^2}{c^2} = \dfrac{2(c-v)}{c} = \dfrac{2[c-(1-\Delta)c]}{c} = 2\Delta.$ Solving for Δ

gives $\Delta = \dfrac{1-v^2/c^2}{2} = \dfrac{\frac{1}{(7.45\times 10^3)^2}}{2} = 9.0\times 10^{-9}.$

(b) Using the relativistic mass formula and the result that $\dfrac{1}{\sqrt{1-v^2/c^2}} = 7.45\times 10^3,$ we have

$m_{\text{rel}} = \dfrac{m}{\sqrt{1-v^2/c^2}} = m\left(\dfrac{1}{\sqrt{1-v^2/c^2}}\right) = (7.5\times 10^3)m.$

EVALUATE: At such high speeds, the proton's mass is 7500 times as great as its rest mass.

37.50. **IDENTIFY** and **SET UP:** The acceleration parallel to the direction of the force is given by $F_{\parallel} = \gamma^3 m a_{\parallel}$, and the acceleration perpendicular to the direction of the force is given by $F_{\perp} = \gamma m a_{\perp}$, where $\gamma = 1/\sqrt{1 - v^2/c^2}$.

EXECUTE: Applying the above formulas to the conditions of this problem, we have $\gamma = 1/\sqrt{1-(0.700)^2} = 1.400$, $F_x = F\cos(30.0°) = \gamma^3 m a_x$ and $F_y = F\sin(30.0°) = \gamma m a_y$. The angle θ that the acceleration makes with respect to the x-axis is given by $\tan\theta = a_y/a_x$. Dividing the acceleration given by the two force equations gives

$$\tan\theta = \frac{\dfrac{F\sin(30.0°)}{\gamma m}}{\dfrac{F\cos(30.0°)}{\gamma^3 m}} = \gamma^2 \tan(30.0°) = (1.400)^2 \tan(30.0°) = 1.132 \qquad \rightarrow \qquad \theta = 48.5°.$$

The acceleration makes a counterclockwise angle of 48.5° from the +x-axis. Therefore it makes an angle of 18.5° counterclockwise from the direction of the force.

EVALUATE: Notice that the acceleration is not in the same direction as the force.

37.51. **IDENTIFY** and **SET UP:** The clock on the plane measures the proper time Δt_0.

$\Delta t = 4.00\text{ h} = (4.00\text{ h})(3600\text{ s}/1\text{ h}) = 1.44\times10^4\text{ s}.$

$\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}}$ and $\Delta t_0 = \Delta t\sqrt{1-u^2/c^2}$.

EXECUTE: $\dfrac{u}{c}$ small so $\sqrt{1-u^2/c^2} = (1-u^2/c^2)^{1/2} \approx 1 - \frac{1}{2}\dfrac{u^2}{c^2}$; thus $\Delta t_0 = \Delta t\left(1 - \dfrac{1}{2}\dfrac{u^2}{c^2}\right)$.

The difference in the clock readings is

$\Delta t - \Delta t_0 = \frac{1}{2}\dfrac{u^2}{c^2}\Delta t = \frac{1}{2}\left(\dfrac{250\text{ m/s}}{2.998\times10^8\text{ m/s}}\right)^2 (1.44\times10^4\text{ s}) = 5.01\times10^{-9}\text{ s}.$ The clock on the plane has the shorter elapsed time.

EVALUATE: Δt_0 is always less than Δt; our results agree with this. The speed of the plane is much less than the speed of light, so the difference in the reading of the two clocks is very small.

37.52. **IDENTIFY:** In the rest frame of the spaceship the trip takes $\Delta t_0 = 3.35$ years.

SET UP: As seen from the earth the trip takes $\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}}$. The distance to the star is 7.11 ly and the speed of light is $c = 1$ ly/y. Let u be the speed of the spaceship (in ly/y) as seen from the earth.

EXECUTE: **(a)** The time for the trip as seen from the earth will be $\Delta t = \dfrac{7.11\text{ ly}}{u} = \dfrac{3.35\text{ y}}{\sqrt{1-u^2/c^2}}$. Solving for u we obtain $\left(\dfrac{7.11\text{ ly}}{3.35\text{ y}}\right)^2(1-u^2/c^2) = u^2$, which reduces to

$u = \left(\dfrac{7.11\text{ ly}}{3.35\text{ y}}\right)\cdot\dfrac{1}{\sqrt{1+\left(\dfrac{7.11\text{ ly}}{(3.35\text{ y})(1\text{ ly/y})}\right)^2}} = 0.905\text{ ly/y} = 0.905c.$ Thus, as seen from the earth, the trip takes

$\dfrac{7.11\text{ ly}}{u} = \dfrac{7.11\text{ ly}}{0.905\text{ ly/y}} = 7.86$ years.

(b) According to the passengers the distance is given by $x' = u\Delta t_0 = (0.905\text{ ly/y})(3.35\text{ y}) = 3.03\text{ ly}$.

EVALUATE: The distance to the star as seen by the passengers could also be calculated by using the length contraction formula: $l = l_0\sqrt{1-u^2/c^2}$.

37.53. IDENTIFY and SET UP: In crown glass the speed of light is $v = \frac{c}{n}$. Calculate the kinetic energy of an electron that has this speed.

EXECUTE: $v = \frac{2.998\times 10^8 \text{ m/s}}{1.52} = 1.972\times 10^8 \text{ m/s}.$

$K = mc^2(\gamma - 1).$

$mc^2 = (9.109\times 10^{-31} \text{ kg})(2.998\times 10^8 \text{ m/s})^2 = 8.187\times 10^{-14} \text{ J}(1 \text{ eV}/1.602\times 10^{-19} \text{ J}) = 0.5111 \text{ MeV}.$

$$\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} = \frac{1}{\sqrt{1 - ((1.972\times 10^8 \text{ m/s})/(2.998\times 10^8 \text{ m/s}))^2}} = 1.328.$$

$K = mc^2(\gamma - 1) = (0.5111 \text{ MeV})(1.328 - 1) = 0.168 \text{ MeV}.$

EVALUATE: No object can travel faster than the speed of light in vacuum but there is nothing that prohibits an object from traveling faster than the speed of light in some material.

37.54. IDENTIFY and SET UP: Use the relativistic formula for momentum $p = \frac{mv}{\sqrt{1 - v^2/c^2}}$.

EXECUTE: Solving for m we obtain

$$m = \frac{p\sqrt{1 - v^2/c^2}}{v} = \frac{(2.52\times 10^{-19} \text{ kg}\cdot\text{m/s})}{1.35\times 10^8 \text{ m/s}}\sqrt{1 - \left(\frac{1.35\times 10^8 \text{ m/s}}{3.00\times 10^8 \text{ m/s}}\right)^2} = 1.67\times 10^{-27} \text{ kg}.$$ The only known positively charged particle with this mass is a proton.

EVALUATE: We cannot use $p = mv$ to find the mass of the particle due to its high speed.

37.55. IDENTIFY and SET UP: The energy released is $E = (\Delta m)c^2$. $\Delta m = \left(\frac{1}{10^4}\right)(12.0 \text{ kg})$. $P_{\text{av}} = \frac{E}{t}$.

The change in gravitational potential energy is $mg\Delta y$.

EXECUTE: (a) $E = (\Delta m)c^2 = \left(\frac{1}{10^4}\right)(12.0 \text{ kg})(3.00\times 10^8 \text{ m/s})^2 = 1.08\times 10^{14} \text{ J}.$

(b) $P_{\text{av}} = \frac{E}{t} = \frac{1.08\times 10^{14} \text{ J}}{4.00\times 10^{-6} \text{ s}} = 2.70\times 10^{19} \text{ W}.$

(c) $E = \Delta U = mg\Delta y$. $m = \frac{E}{g\Delta y} = \frac{1.08\times 10^{14} \text{ J}}{(9.80 \text{ m/s}^2)(1.00\times 10^3 \text{ m})} = 1.10\times 10^{10} \text{ kg}.$

EVALUATE: The mass decrease is only 1.2 grams, but the energy released is very large.

37.56. IDENTIFY: The protons are moving at speeds that are comparable to the speed of light, so we must use the relativistic velocity addition formula.

SET UP: S is lab frame and S' is frame of proton moving in $+x$-direction. $v_x = -0.700c$. In lab frame each proton has speed αc. $u = +\alpha c$. $v_x = -\alpha c$. $v_x = \frac{v_x' + u}{1 + uv_x'/c^2} = \frac{-0.700c + \alpha c}{1 - 0.700\alpha} = -\alpha c.$

EXECUTE: $(1 - 0.700\alpha)(-\alpha) = -0.700 + \alpha$. $0.700\alpha^2 - 2\alpha + 0.700 = 0$. The quadratic formula gives $\alpha = 2.45$ or $\alpha = 0.408$. We cannot have $v > c$ so $\alpha = 0.408$. Each proton has speed $0.408c$ in the earth frame.

EVALUATE: To the earth observer, the protons are separating at $2(0.408c) = 0.816c$, but to the protons they are separating at $0.700c$.

37.57. IDENTIFY and SET UP: Let S be the lab frame and let S' be the frame of the nucleus. Let the $+x$-direction be the direction the nucleus is moving. $u = 0.7500c$.

EXECUTE: (a) $v' = +0.9995c$. $v = \frac{v' + u}{1 + uv'/c^2} = \frac{0.9995c + 0.7500c}{1 + (0.7500)(0.9995)} = 0.999929c.$

(b) $v' = -0.9995c.$ $v = \dfrac{-0.9995c + 0.7500c}{1+(0.7500)(-0.9995)} = -0.9965c.$

(c) emitted in same direction:

(i) $K = \left(\dfrac{1}{\sqrt{1-v^2/c^2}} - 1\right)mc^2 = (0.511\text{ MeV})\left(\dfrac{1}{\sqrt{1-(0.999929)^2}} - 1\right) = 42.4\text{ MeV}.$

(ii) $K' = \left(\dfrac{1}{\sqrt{1-v^2/c^2}} - 1\right)mc^2 = (0.511\text{ MeV})\left(\dfrac{1}{\sqrt{1-(0.9995)^2}} - 1\right) = 15.7\text{ MeV}.$

(d) emitted in opposite direction:

(i) $K = \left(\dfrac{1}{\sqrt{1-v^2/c^2}} - 1\right)mc^2 = (0.511\text{ MeV})\left(\dfrac{1}{\sqrt{1-(0.9965)^2}} - 1\right) = 5.60\text{ MeV}.$

(ii) $K' = \left(\dfrac{1}{\sqrt{1-v^2/c^2}} - 1\right)mc^2 = (0.511\text{ MeV})\left(\dfrac{1}{\sqrt{1-(0.9995)^2}} - 1\right) = 15.7\text{ MeV}.$

EVALUATE: The kinetic energy in the frame of the nucleus is the same in both cases since this is the proper frame.

37.58. **IDENTIFY:** Apply the Lorentz coordinate transformation.
SET UP: Let t and t' be time intervals between the events as measured in the two frames and let x and x' be the difference in the positions of the two events as measured in the two frames.
EXECUTE: Setting $x = 0$ in the Lorentz transformation equations, the first equation becomes $x' = -\gamma ut$ and the last, upon multiplication by c, becomes $ct' = \gamma ct$. Squaring and subtracting gives $c^2t'^2 - x'^2 = \gamma^2 t^2 (c^2 - u^2)$. But $\gamma^2 = c^2/(c^2 - v^2)$, so $\gamma^2 t^2 (c^2 - v^2) = c^2 t^2$. Therefore, $c^2t'^2 - x'^2 = c^2t^2$ which gives $x' = c\sqrt{t'^2 - t^2} = c\sqrt{(2.15\text{ s})^2 - (1.80\text{ s})^2} = 3.53\times 10^8\text{ m}.$
EVALUATE: We did not have to calculate the speed u of frame S' relative to frame S.

37.59. **IDENTIFY** and **SET UP:** An increase in wavelength corresponds to a decrease in frequency $(f = c/\lambda)$, so the atoms are moving away from the earth. The galaxy is receding, so we use $f = \sqrt{\dfrac{c-u}{c+u}}f_0$.

EXECUTE: Solve for u: $(f/f_0)^2(c+u) = c - u$ and $u = c\left(\dfrac{1-(f/f_0)^2}{1+(f/f_0)^2}\right)$.

$f = c/\lambda,\ f_0 = c/\lambda_0$ so $f/f_0 = \lambda_0/\lambda.$

$u = c\left(\dfrac{1-(\lambda_0/\lambda)^2}{1+(\lambda_0/\lambda)^2}\right) = c\left(\dfrac{1-(656.3/953.4)^2}{1+(656.3/953.4)^2}\right) = 0.357c = 1.07\times 10^8\text{ m/s}.$

EVALUATE: The relative speed is large, 36% of c. The cosmological implication of such observations will be discussed in Chapter 44.

37.60. **IDENTIFY:** Apply the relativistic expressions for kinetic energy, velocity transformation, length contraction and time dilation.
SET UP: In part (c) let S' be the earth frame and let S be the frame of the ball. Let the direction from Einstein to Lorentz be positive, so $u = -1.80\times 10^8$ m/s. In part (d) the proper length is $l_0 = 20.0$ m and in part (f) the proper time is measured by the rabbit.
EXECUTE: **(a)** 80.0 m/s is nonrelativistic, and $K = \frac{1}{2}mv^2 = 186$ J.

(b) $K = (\gamma - 1)mc^2 = 1.31\times 10^{15}$ J.

(c) In Eq. (37.23), $v' = 2.20\times 10^8$ m/s, $u = -1.80\times 10^8$ m/s, and so $v = 7.14\times 10^7$ m/s.

(d) $l = \dfrac{l_0}{\gamma} = \dfrac{20.0\text{ m}}{\gamma} = 13.6\text{ m}.$

(e) $\dfrac{20.0\text{ m}}{2.20\times10^{8}\text{ m/s}} = 9.09\times10^{-8}\text{ s}.$

(f) $\Delta t_0 = \dfrac{\Delta t}{\gamma} = 6.18\times10^{-8}\text{ s}$

EVALUATE: In part (f) we could also calculate Δt_0 as $\Delta t_0 = \dfrac{13.6\text{ m}}{2.20\times10^{8}\text{ m/s}} = 6.18\times10^{-8}\text{ s}.$

37.61. IDENTIFY: The baseball is moving toward the radar gun, so apply the Doppler effect equation $f = \sqrt{\dfrac{c+u}{c-u}}f_0.$

SET UP: The baseball had better be moving nonrelativistically, so the Doppler shift formula becomes $f \cong f_0(1-(u/c)).$ In the baseball's frame, this is the frequency with which the radar waves strike the baseball, and the baseball reradiates at *f.* But in the coach's frame, the reflected waves are Doppler shifted again, so the detected frequency is $f(1-(u/c)) = f_0(1-(u/c))^2 \approx f_0(1-2(u/c)).$

EXECUTE: $\Delta f = 2f_0(u/c)$ and the fractional frequency shift is $\dfrac{\Delta f}{f_0} = 2(u/c).$

$$u = \frac{\Delta f}{2f_0}c = \frac{(2.86\times10^{-7})}{2}(3.00\times10^{8}\text{ m}) = 42.9\text{ m/s} = 154\text{ km/h} = 92.5\text{ mi/h}.$$

EVALUATE: $u \ll c,$ so using the approximate expression in place of $f = \sqrt{\dfrac{c+u}{c-u}}f_0$ is very accurate.

37.62. IDENTIFY and **SET UP:** For part (a) follow the procedure specified in the hint. For part (b) apply $f = \sqrt{\dfrac{c+u}{c-u}}f_0$ and $f = \sqrt{\dfrac{c-u}{c+u}}f_0.$

EXECUTE: **(a)** As in the hint, both the sender and the receiver measure the same distance. However, in our frame, the ship has moved between emission of successive wavefronts, and we can use the time $T = 1/f$ as the proper time, with the result that $f = \gamma f_0 > f_0.$

(b) Toward: $f_1 = f_0\sqrt{\dfrac{c+u}{c-u}} = 345\text{ MHz}\left(\dfrac{1+0.758}{1-0.758}\right)^{1/2} = 930\text{ MHz}$ and

$f_1 - f_0 = 930\text{ MHz} - 345\text{ MHz} = 585\text{ MHz}.$

Away: $f_2 = f_0\sqrt{\dfrac{c-u}{c+u}} = 345\text{ MHz}\left(\dfrac{1-0.758}{1+0.758}\right)^{1/2} = 128\text{ MHz}$ and $f_2 - f_0 = -217\text{ MHz}.$

(c) $f_3 = \gamma f_0 = 1.53f_0 = 528\text{ MHz}, f_3 - f_0 = 183\text{ MHz}.$

EVALUATE: The frequency in part (c) is the average of the two frequencies in part (b). A little algebra shows that f_3 is precisely equal to $(f_1 + f_2)/2.$

37.63. IDENTIFY: We need to use the relativistic form of Newton's second law because the speed of the proton is close to the speed of light.

SET UP: $\vec{F}$ and $\vec{v}$ are perpendicular, so $F = \gamma ma = \gamma m\dfrac{v^2}{R}.$ $\gamma = \dfrac{1}{\sqrt{1-v^2/c^2}} = \dfrac{1}{\sqrt{1-(0.750)^2}} = 1.512.$

EXECUTE: $F = (1.512)(1.67\times10^{-27}\text{ kg})\dfrac{[(0.750)(3.00\times10^{8}\text{ m/s}]^2}{628\text{ m}} = 2.04\times10^{-13}\text{ N}.$

EVALUATE: If we ignored relativity, the force would be

$F_{\text{rel}}/\gamma = \dfrac{2.04\times10^{-13}\text{ N}}{1.512} = 1.35\times10^{-13}\text{ N},$ which is substantially less than the relativistic force.

37.64. IDENTIFY: Apply the Lorentz velocity transformation.

SET UP: Let the tank and the light both be traveling in the $+x$-direction. Let *S* be the lab frame and let S' be the frame of the tank of water.

EXECUTE: In the equation $v_x = \dfrac{v'_x + u}{1 + uv'_x/c^2}$, $u = V$, $v' = (c/n)$. $v = \dfrac{(c/n)+V}{1+\dfrac{cV}{nc^2}} = \dfrac{(c/n)+V}{1+(V/nc)}$. For $V \ll c$,

$(1+V/nc)^{-1} \approx (1-V/nc)$. This gives

$v \approx [(c/n)+V][1-(V/nc)] = c/n + V - (V/n^2) - (V^2/nc) \approx \dfrac{c}{n} + \left(1-\dfrac{1}{n^2}\right)V$, so $k = \left(1-\dfrac{1}{n^2}\right)$. For water, $n = 1.333$ and $k = 0.437$.

EVALUATE: The Lorentz transformation predicts a value of *k* in excellent agreement with the value that is measured experimentally.

37.65. IDENTIFY and SET UP: The equation $\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}}$ relates the time interval in the laboratory (Δt) to the time interval (Δt_0) in the rest frame of the particle.

EXECUTE: **(a)** Solve the above equation for $(\Delta t)^2$. Squaring gives $(\Delta t)^2 = (\Delta t_0)^2(1-u^2/c^2)^{-1}$. Therefore a graph of $(\Delta t)^2$ versus $(1-u^2/c^2)^{-1}$ should be a straight line with slope equal to $(\Delta t_0)^2$. Figure 37.65 shows this graph for the data in the problem. The slope of the best-fit straight line is 0.6709×10^{-15} s^2, so $\Delta t_0 = \sqrt{0.6709\times10^{-15}\ \text{s}^2} = 2.6\times10^{-8}$ s = 26 ns.

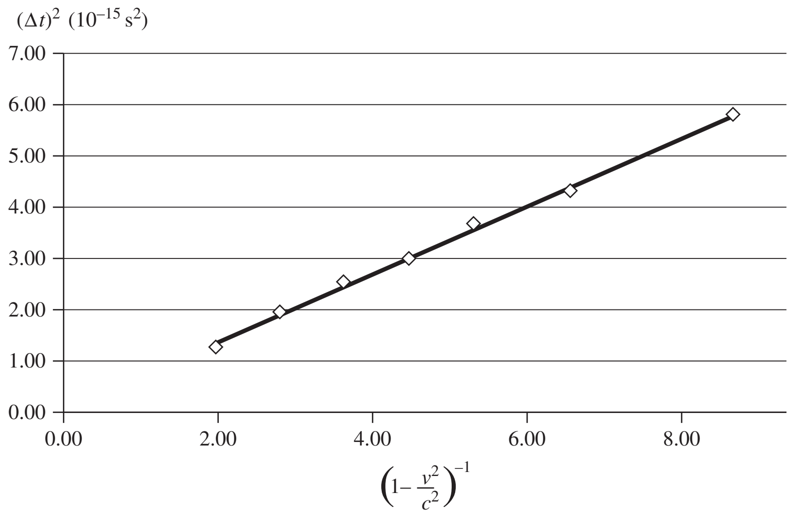


Figure 37.65

(b) Using $\Delta t = 4\,\Delta t_0$, the equation $\Delta t = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}}$ gives $4\Delta t_0 = \dfrac{\Delta t_0}{\sqrt{1-u^2/c^2}}$. Solving for *u/c* gives *u/c* = 0.97.

EVALUATE: At speeds near the speed of light, there is a very large difference between the lifetime measured in the laboratory frame compared to the lifetime in the rest frame of the particle.

37.66. IDENTIFY: Relative motion between the observer and the source of electromagnetic waves affects the frequency received by the observer due to the Doppler effect. If the source is moving toward the observer with speed *u* and emitting frequency f_0, the frequency *f* that the observer receives is given by $f = f_0\sqrt{\dfrac{c+u}{c-u}}$, and if it is moving away the formula is $f = f_0\sqrt{\dfrac{c-u}{c+u}}$. Notice that $f > f_0$.

SET UP: In this case, we know *f* and f_0 and want to find *u*. Looking at the data given in the problem, we see that $f < f_0$, which means that the source must be moving *away from* the observer, so we use $f = f_0\sqrt{\dfrac{c-u}{c+u}}$. Solve the equation $f = f_0\sqrt{\dfrac{c-u}{c+u}}$ for *u*, since we know the frequencies. This gives

$$u=\left(\frac{f_0^2-f^2}{f_0^2+f^2}\right)c.$$

EXECUTE: **(a)** To see which source is moving fastest, look at f_0/f; the larger this ratio, the greater the speed u.

For A: $f_0/f = 9.2/7.1 = 1.30$.
For B: $f_0/f = 8.6/5.4 = 1.59$.
For C: $f_0/f = 7.9/6.1 = 1.30$.
For D: $f_0/f = 8.9/8.1 = 1.10$.

Therefore source B is moving fastest and source D is moving slowest. The speed of B is

$$u=\left(\frac{(8.6\text{ THz})^2-(5.4\text{ THz})^2}{(8.6\text{ THz})^2+(5.4\text{ THz})^2}\right)c=0.434c,$$ which rounds to $0.43c$, away from the detector.

(b) The speed for source D is $u=\left(\frac{(8.9\text{ THz})^2-(8.1\text{ THz})^2}{(8.9\text{ THz})^2+(8.1\text{ THz})^2}\right)c=0.094c,$ away from the detector.

(c) Since B is now approaching the detector, we use $f=f_0\sqrt{\frac{c+u}{c-u}}$ with $u = 0.434c$ and $f_0 = 8.6$ THz. This gives $f=f_0\sqrt{\frac{c+u}{c-u}}=(8.6\text{ THz})\sqrt{\frac{1+0.434}{1-0.434}}$ = 14 THz = 1.4×10^{13} Hz.

EVALUATE: The change in observed frequency is small for low speeds but increases dramatically as $u\to c$.

37.67. IDENTIFY and **SET UP:** When the force on a particle is along the same line as its velocity, the force and acceleration are related by $F=\gamma^3ma$, where $\gamma=1/\sqrt{1-v^2/c^2}$.

EXECUTE: **(a)** Solve the equation $F=\gamma^3ma$ for a^2.

$$a=\frac{F}{m\gamma^3}=\frac{F}{m}\left(1-\frac{v^2}{c^2}\right)^{3/2} \quad\rightarrow\quad a^2=\left(\frac{F}{m}\right)^2\left(1-\frac{v^2}{c^2}\right)^3.$$

From this result we see that a graph of a^2 versus $\left(1-\frac{v^2}{c^2}\right)^3$ should be a straight line with slope equal to $(F/m)^2$. Figure 37.67 shows the graph of the data in the table with the problem. It is well fit by a straight line having slope equal to 1.608×10^9 m^2/s^4. Therefore the mass is

$$(F/m)^2=\text{slope} \quad\rightarrow\quad m=\frac{F}{\sqrt{\text{slope}}}=\frac{8.00\times10^{-14}\text{ N}}{\sqrt{1.608\times10^9\text{ m}^2/\text{s}^4}}=2.0\times10^{-18}\text{ kg}.$$

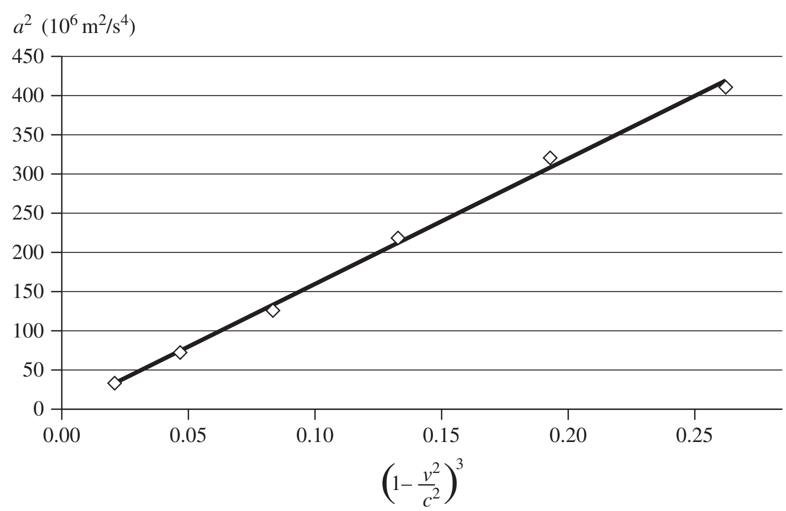


Figure 37.67

(b) In this case, $v << c$, so γ is essentially equal to 1. Therefore we can use the familiar form of Newton's second law, $F = ma$.
$a = F/m = (8.00\times10^{-14}\text{ N})/(2.0\times10^{-18}\text{ kg}) = 4.0\times10^{4}\text{ m/s}^2$.
EVALUATE: When v is close to c, $a = F/m$ does not give the correct result. For example, using data from the table in the problem, when $v/c = 0.85$, the acceleration is measured to be 5900 m/s^2. But using the familiar Newtonian formula we get $a = F/m = (8.00\times10^{-14}\text{ N})/(2.0\times10^{-18}\text{ kg}) = 4.0\times10^{4}\text{ m/s}^2 = 40{,}000$ m/s^2, which is *very* different from the relativistic result of 5900 m/s^2.

37.68. **IDENTIFY:** Apply the Doppler effect equation.
SET UP: At the two positions shown in the figure given in the problem, the velocities of the star relative to the earth are $u+v$ and $u-v$, where u is the velocity of the center of mass and v is the orbital velocity.
EXECUTE: **(a)** $f_0 = 4.568110\times10^{14}$ Hz; $f_+ = 4.568910\times10^{14}$ Hz; $f_- = 4.567710\times10^{14}$ Hz.

$$\left.\begin{aligned} f_+ &= \sqrt{\frac{c+(u+v)}{c-(u+v)}}f_0 \\ f_- &= \sqrt{\frac{c+(u-v)}{c-(u-v)}}f_0 \end{aligned}\right\} \Rightarrow \begin{aligned} f_+^2(c-(u+v)) &= f_0^2\,(c+(u+v)) \\ f_-^2(c-(u-v)) &= f_0^2(c+(u-v)) \end{aligned}$$

$(u+v) = \dfrac{(f_+/f_0)^2-1}{(f_+/f_0)^2+1}c$ and $(u-v) = \dfrac{(f_-^2/f_0^2)-1}{(f_-^2/f_0^2)+1}c$. $u+v = 5.25\times10^4$ m/s and $u-v = -2.63\times10^4$ m/s.

This gives $u = +1.31\times10^4$ m/s (moving toward at 13.1 km/s) and $v = 3.94\times10^4$ m/s.

(b) $v = 3.94\times10^4$ m/s; $T = 11.0$ days. $2\pi R = vt \Rightarrow$

$$R = \frac{(3.94\times10^4\text{ m/s})(11.0\text{ days})(24\text{ hrs/day})(3600\text{ sec/hr})}{2\pi} = 5.96\times10^9\text{ m}.$$ This is about 0.040 times the earth-sun distance.

Also the gravitational force between them (a distance of $2R$) must equal the centripetal force from the center of mass:

$$\frac{(Gm^2)}{(2R)^2} = \frac{mv^2}{R} \Rightarrow m = \frac{4Rv^2}{G} = \frac{4(5.96\times10^9\text{ m})(3.94\times10^4\text{ m/s})^2}{6.672\times10^{-11}\text{ N}\cdot\text{m}^2/\text{kg}^2} = 5.55\times10^{29}\text{ kg} = 0.279\, m_\text{sun}.$$

EVALUATE: u and v are both much less than c, so we could have used the approximate expression $\Delta f = \pm f_0 v_\text{rev}/c$, where v_rev is the speed of the source relative to the observer.

37.69. **IDENTIFY:** Apply conservation of total energy, in the frame in which the total momentum is zero (the center of momentum frame).
SET UP: In the center of momentum frame, the two protons approach each other with equal velocities (since the protons have the same mass). After the collision, the two protons are at rest—but now there are kaons as well. In this situation the kinetic energy of the protons must equal the total rest energy of the two kaons.

EXECUTE: **(a)** $2(\gamma_\text{cm}-1)m_\text{p}c^2 = 2m_\text{k}c^2 \Rightarrow \gamma_\text{cm} = 1+\dfrac{m_\text{k}}{m_\text{p}} = 1.526.$ The velocity of a proton in the center of momentum frame is then $v_\text{cm} = c\sqrt{\dfrac{\gamma_\text{cm}^2-1}{\gamma_\text{cm}^2}} = 0.7554c.$

To get the velocity of this proton in the lab frame, we must use the Lorentz velocity transformations. This is the same as "hopping" into the proton that will be our target and asking what the velocity of the projectile proton is. Taking the lab frame to be the unprimed frame moving to the left, $u = v_\text{cm}$ and $v' = v_\text{cm}$ (the velocity of the projectile proton in the center of momentum frame).

$$v_\text{lab} = \frac{v'+u}{1+\frac{uv'}{c^2}} = \frac{2v_\text{cm}}{1+\frac{v_\text{cm}^2}{c^2}} = 0.9619c \Rightarrow \gamma_\text{lab} = \frac{1}{\sqrt{1-\frac{v_\text{lab}^2}{c^2}}} = 3.658 \Rightarrow K_\text{lab} = (\gamma_\text{lab}-1)m_\text{p}c^2 = 2494\text{ MeV}.$$

(b) $\dfrac{K_{\text{lab}}}{2m_{\text{k}}} = \dfrac{2494\text{ MeV}}{2(493.7\text{ MeV})} = 2.526.$

(c) The center of momentum case considered in part (a) is the same as this situation. Thus, the kinetic energy required *is* just twice the rest mass energy of the kaons. $K_{\text{cm}} = 2(493.7\text{ MeV}) = 987.4\text{ MeV}.$

EVALUATE: The colliding beam situation of part (c) offers a substantial advantage over the fixed target experiment in part (b). It takes less energy to create two kaons in the proton center of momentum frame.

37.70. IDENTIFY and **SET UP:** Apply the procedures specified in the problem.

EXECUTE: For any function $f = f(x,t)$ and $x = x(x',t'), t = t(x',t')$, let $F(x',t') = f(x(x',t'), t(x',t'))$ and use the standard (but mathematically improper) notation $F(x',t') = f(x',t')$. The chain rule is then

$$\frac{\partial f(x',t')}{\partial x} = \frac{\partial f(x,t)}{\partial x'}\frac{\partial x'}{\partial x} + \frac{\partial f(x',t')}{\partial t'}\frac{\partial t'}{\partial x},$$
$$\frac{\partial f(x',t')}{\partial t} = \frac{\partial f(x,t)}{\partial x'}\frac{\partial x'}{\partial t} + \frac{\partial f(x',t')}{\partial x'}\frac{\partial t'}{\partial t}.$$

In this solution, the explicit dependence of the functions on the sets of dependent variables is suppressed, and the above relations are then $\dfrac{\partial f}{\partial x} = \dfrac{\partial f}{\partial x'}\dfrac{\partial x'}{\partial x} + \dfrac{\partial f}{\partial t'}\dfrac{\partial t'}{\partial x}$, $\dfrac{\partial f}{\partial t} = \dfrac{\partial f}{\partial x'}\dfrac{\partial x'}{\partial t} + \dfrac{\partial f}{\partial t'}\dfrac{\partial t'}{\partial t}.$

(a) $\dfrac{\partial x'}{\partial x} = 1, \dfrac{\partial x'}{\partial t} = -v, \dfrac{\partial t'}{\partial x} = 0$ and $\dfrac{\partial t'}{\partial t} = 1.$ Then, $\dfrac{\partial E}{\partial x} = \dfrac{\partial E}{\partial x'}$, and $\dfrac{\partial^2 E}{\partial x^2} = \dfrac{\partial^2 E}{\partial x'^2}.$ For the time derivative, $\dfrac{\partial E}{\partial t} = -v\dfrac{\partial E}{\partial x'} + \dfrac{\partial E}{\partial t'}.$ To find the second time derivative, the chain rule must be applied to both terms; that is,

$$\frac{\partial}{\partial t}\frac{\partial E}{\partial x'} = -v\frac{\partial^2 E}{\partial x'^2} + \frac{\partial^2 E}{\partial t' \partial x'},$$
$$\frac{\partial}{\partial t}\frac{\partial E}{\partial t'} = -v\frac{\partial^2 E}{\partial x' \partial t'} + \frac{\partial^2 E}{\partial t'^2}.$$

Using these in $\dfrac{\partial^2 E}{\partial t^2}$, collecting terms and equating the mixed partial derivatives gives

$\dfrac{\partial^2 E}{\partial t^2} = v^2\dfrac{\partial^2 E}{\partial x'^2} - 2v\dfrac{\partial^2 E}{\partial x' \partial t'} + \dfrac{\partial^2 E}{\partial t'^2}$, and using this and the above expression for $\dfrac{\partial^2 E}{\partial x'^2}$ gives the result.

(b) For the Lorentz transformation, $\dfrac{\partial x'}{\partial x} = \gamma, \dfrac{\partial x'}{\partial t} = \gamma v, \dfrac{\partial t'}{\partial x} = \gamma v/c^2$ and $\dfrac{\partial t'}{\partial t} = \gamma.$

The first partials are then

$$\frac{\partial E}{\partial x} = \gamma\frac{\partial E}{\partial x'} - \gamma\frac{v}{c^2}\frac{\partial E}{\partial t'}, \frac{\partial E}{\partial t} = -\gamma v\frac{\partial E}{\partial x'} + \gamma\frac{\partial E}{\partial t'}$$

and the second partials are (again equating the mixed partials)

$$\frac{\partial^2 E}{\partial x^2} = \gamma^2\frac{\partial^2 E}{\partial x'^2} + \gamma^2\frac{v^2}{c^4}\frac{\partial^2 E}{\partial t'^2} - 2\gamma^2\frac{v}{c^2}\frac{\partial^2 E}{\partial x' \partial t'}$$
$$\frac{\partial^2 E}{\partial t^2} = \gamma^2 v^2\frac{\partial^2 E}{\partial x'^2} + \gamma^2\frac{\partial^2 E}{\partial t'^2} - 2\gamma^2 v\frac{\partial^2 E}{\partial x' \partial t'}.$$

Substituting into the wave equation and combining terms (note that the mixed partials cancel),

$$\frac{\partial^2 E}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \gamma^2\left(1 - \frac{v^2}{c^2}\right)\frac{\partial^2 E}{\partial x'^2} + \gamma^2\left(\frac{v^2}{c^4} - \frac{1}{c^2}\right)\frac{\partial^2 E}{\partial t'^2} = \frac{\partial^2 E}{\partial x'^2} - \frac{1}{c^2}\frac{\partial^2 E}{\partial t'^2} = 0.$$

EVALUATE: The general form of the wave equation is given by Eq. (32.1). The coefficient of the $\partial^2/\partial t^2$ term is the inverse of the square of the wave speed. This coefficient is the same in both frames, so the wave speed is the same in both frames.

37.71. **IDENTIFY and SET UP:** The relativity formulas apply, but c = 300 m/s in this universe. $\gamma = 1/\sqrt{1 - v^2/c^2}$ = $1/\sqrt{1-(180\text{ m/s})^2/(300\text{ m/s})^2} = 1.25$. The length is $l = l_0/\gamma$.

EXECUTE: $l = l_0/\gamma$ = (60 m)/(1.25) = 48 m, choice (c).

EVALUATE: Relativistic effects would be "common sense" in this universe!

37.72. **IDENTIFY and SET UP:** The relativity formulas apply, but c = 300 m/s in this universe. $\gamma = 1/\sqrt{1 - v^2/c^2}$ = $1/\sqrt{1-(180\text{ m/s})^2/(300\text{ m/s})^2} = 1.40$.

EXECUTE: The relativistic mass is $m\gamma$ = (20,000 kg)(1.25) = 25,000 kg, choice (d).

EVALUATE: The relativistic mass of the passengers and their luggage would also be greater by the factor 1.25, so excess baggage fees could be rather common.

37.73. **IDENTIFY:** The rest energy is $E_0 = mc^2$.

SET UP: In our universe, $E_0 = mc^2$ and in the alternative universe the same formula would apply, except that c would be different, call it c', so $E_0' = mc'^2$. Therefore $E_0' = \left(\dfrac{E_0}{c^2}\right)c'^2$.

EXECUTE: $E_0' = \left(\dfrac{E_0}{c^2}\right)c'^2 = \left(\dfrac{8.2\times10^{-14}\text{ J}}{(3.0\times10^8\text{ m/s})^2}\right)(300\text{ m/s})^2 = 8.2\times10^{-26}\text{ J}$, choice (b).

EVALUATE: The rest energy of all other particles would be reduced by the same fraction in this alternate universe.

37.74. **IDENTIFY and SET UP:** The kinetic energy is $K = (\gamma - 1)mc^2$.

EXECUTE: The kinetic energy is now equal to the rest energy, so $K = (\gamma - 1)mc^2 = mc^2$, which means that $\gamma = 2$. Therefore $2 = 1/\sqrt{1 - v^2/c^2}$. Solving for v gives $v = c\sqrt{1-(1/2)^2} = (300\text{ m/s})\sqrt{3/4} = 260$ m/s, choice (b).

EVALUATE: Airplanes and rockets would certainly need to take relativistic effects into consideration in this alternative universe!