

3

Relativistic Kinematics

In this chapter, I summarize the basic principles, notation, and terminology of relativistic kinematics. This is material you must know cold in order to understand Chapters 6 through 10 (it is not needed for Chapters 4 and 5, however, and if you prefer you can read them first). Although the treatment is reasonably self-contained, I do assume that you have encountered special relativity before – if not, you should pause here and read the appropriate chapter in any introductory physics text before proceeding. If you are already quite familiar with relativity, this chapter will be an easy review – but read through it anyway because some of the notation may be new to you.

3.1

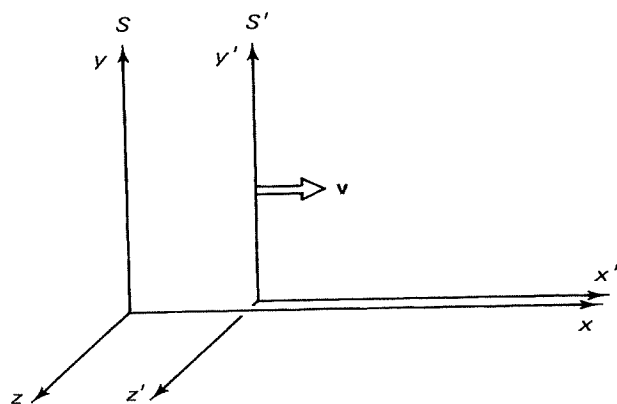
Lorentz Transformations

According to the special theory of relativity [1], the laws of physics apply just as well in a reference system moving at constant velocity as they do in one at rest. An embarrassing implication of this is that there's no way of telling which system (if any) is at rest, and hence there is no way of knowing what 'the' velocity of any other system might be. So perhaps I had better start over. *Ahem.*

According to the special theory of relativity [1], the laws of physics are equally valid in all *inertial* reference systems. An inertial system is one in which Newton's first law (the law of inertia) is obeyed: objects keep moving in straight lines at constant speeds unless acted upon by some force.* It's easy to see that any two inertial systems must be moving at constant velocity with respect to one another, and conversely, that any system moving at constant velocity with respect to an inertial system is itself inertial.

Imagine, then, that we have two inertial frames, S and S' , with S' moving at uniform velocity \mathbf{v} (magnitude v) with respect to S (S , then, is moving at velocity $-\mathbf{v}$ with respect to S'). We may as well lay out our coordinates in such a way that the motion is along the common x/x' axis (Figure 3.1), and set the master clocks at the origin in each system so that both read zero at the instant the two coincide (that is, $t = t' = 0$ when $x = x' = 0$). Suppose, now, that some event occurs at position

* If you are wondering whether a freely falling system in a uniform gravitational field is 'inertial', you know more than is good for you. Let's just keep gravity out of it.

Fig. 3.1 The inertial systems S and S' .

(x, y, z) and time t in S . *Question:* What are the space-time coordinates (x', y', z') and t' of this *same event* in S' ? The answer is provided by the Lorentz transformations:

$$\begin{aligned} \text{i. } x' &= \gamma(x - vt) \\ \text{ii. } y' &= y \\ \text{iii. } z' &= z \\ \text{iv. } t' &= \gamma\left(t - \frac{v}{c^2}x\right) \end{aligned} \quad (3.1)$$

where

$$\gamma \equiv \frac{1}{\sqrt{1 - v^2/c^2}} \quad (3.2)$$

The inverse transformations, which take us back from S' to S , are obtained by simply changing the sign of v (see Problem 3.1):

$$\begin{aligned} \text{i'. } x &= \gamma(x' + vt') \\ \text{ii'. } y &= y' \\ \text{iii'. } z &= z' \\ \text{iv'. } t &= \gamma\left(t' + \frac{v}{c^2}x'\right) \end{aligned} \quad (3.3)$$

The Lorentz transformations have a number of immediate consequences, of which I mention briefly the most important:

1. *The relativity of simultaneity:* If two events occur at the same time in S , but at different locations, then they do *not* occur at the same time in S' . Specifically, if $t_A = t_B$, then

$$t'_A = t'_B + \frac{\gamma v}{c^2}(x_B - x_A) \quad (3.4)$$

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(see Problem 3.2). Events that are simultaneous in one inertial system, then, are not simultaneous in others.

2. *Lorentz contraction*: Suppose a stick lies on the x' axis, at rest in S' . Say one end is at the origin ($x' = 0$) and the other is at L' (so its length in S' is L'). What is its length as measured in S ? Since the stick is *moving* with respect to S , we must be careful to record the positions of its two ends at the same instant, say $t = 0$. At that moment, the left end is at $x = 0$ and the right end, according to Equation (i), is at $x = L'/\gamma$. Thus the length of the stick is $L = L'/\gamma$, in S . Notice that γ is always greater than or equal to 1. It follows that a *moving object is shortened* by a factor of γ , as compared with its length in the system in which it is at rest. Notice that Lorentz contraction only applies to lengths *along the direction of motion*; perpendicular dimensions are not affected.

3. *Time dilation*: Suppose the clock at the origin in S' ticks off an interval T' ; for simplicity, say it runs from $t' = 0$ to $t' = T'$. How long is this period as measured in S ? Well, it begins when $t = 0$, and it ends when $t' = T'$ at $x' = 0$, so (according to Equation (iv')) $t = \gamma T'$. Evidently the clocks in S tick off a *longer* interval, $T = \gamma T'$, by that same factor of γ ; or, put it the other way around: *moving clocks run slow*.

Unlike Lorentz contraction, which is only indirectly relevant to elementary particle physics, time dilation is a commonplace in the laboratory. For, in a sense, every unstable particle has a built-in clock: whatever it is that tells the particle when its time is up. And these internal clocks do indeed run slow when the particle is moving. That is to say, a moving particle lasts longer (by a factor of γ) than it would at rest.* (The tabulated lifetimes are, of course, for particles at rest.) In fact, the cosmic ray muons produced in the upper atmosphere would never make it to ground level were it not for time dilation (see Problem 3.4).

4. *Velocity addition*: Suppose a particle is moving in the x direction at speed u' , with respect to S' . What is its speed, u , with respect to S ? Well, it travels a distance $\Delta x = \gamma(\Delta x' + v \Delta t')$ in a time $\Delta t = \gamma[\Delta t' + (v/c^2)\Delta x']$, so

$$\frac{\Delta x}{\Delta t} = \frac{\Delta x' + v \Delta t'}{\Delta t' + (v/c^2)\Delta x'} = \frac{(\Delta x'/\Delta t') + v}{1 + (v/c^2)(\Delta x'/\Delta t')}.$$

* Actually, the disintegration of an individual particle is a random process; when we speak of a 'lifetime' we really mean the *average* lifetime of that particle type. When I say that a moving particle lasts longer, I really mean that the *average* lifetime of a *group* of moving particles is longer.

But $\Delta x/\Delta t = u$, and $\Delta x'/\Delta t' = u'$, so

$$u = \frac{u' + v}{1 + (u'v/c^2)} \quad (3.5)$$

Notice that if $u' = c$, then $u = c$ also: *the speed of light is the same in all inertial systems.*

It can sometimes be confusing to figure out in a particular context, which numbers should be primed and what signs attach to the velocities, so I personally remember three rules: moving sticks are short (by a factor of γ), moving clocks are slow (by a factor of γ) – so put the γ (which, remember, is *greater* than 1) on whichever side of the equation you need to achieve these results, – and

$$v_{AC} = \frac{v_{AB} + v_{BC}}{1 + (v_{AB}v_{BC}/c^2)} \quad (3.6)$$

where v_{AB} (for instance) means the velocity of A with respect to B. The numerator is the classical result (the so-called ‘Galilean velocity addition rule’); the denominator is Einstein’s correction – it is very close to 1 unless the velocities are close to c .

3.2

Four-vectors

It is convenient at this point to introduce some simplifying notation. We define the *position-time four-vector* x^μ , $\mu = 0, 1, 2, 3$, as follows:

$$x^0 = ct, \quad x^1 = x, \quad x^2 = y, \quad x^3 = z \quad (3.7)$$

In terms of x^μ , the Lorentz transformations take on a more symmetrical appearance:

$$\begin{aligned} x^{0'} &= \gamma(x^0 - \beta x^1) \\ x^{1'} &= \gamma(x^1 - \beta x^0) \\ x^{2'} &= x^2 \\ x^{3'} &= x^3 \end{aligned} \quad (3.8)$$

where

$$\beta \equiv \frac{v}{c} \quad (3.9)$$

More compactly:

$$x^{\mu'} = \sum_{\nu=0}^3 \Lambda_{\nu}^{\mu'} x^{\nu} \quad (\mu = 0, 1, 2, 3) \quad (3.10)$$

The coefficients Λ_{ν}^{μ} may be regarded as the elements of a matrix Λ :

$$\Lambda = \begin{bmatrix} \gamma & -\gamma\beta & 0 & 0 \\ -\gamma\beta & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3.11)$$

(i.e. $\Lambda_0^0 = \Lambda_1^1 = \gamma$; $\Lambda_0^1 = \Lambda_1^0 = -\gamma\beta$; $\Lambda_2^2 = \Lambda_3^3 = 1$; and all the rest are zero). To avoid writing lots of Σ 's, we shall follow Einstein's 'summation convention', which says that repeated Greek indices (one as subscript, one as superscript) are to be summed from 0 to 3. Thus Equation 3.10 becomes, finally,*

$$x^{\mu'} = \Lambda_{\nu}^{\mu} x^{\nu} \quad (3.12)$$

A special virtue of this tidy notation is that the same form describes Lorentz transformations that are *not* along the x direction; in fact, the S and S' axes need not even be parallel; the Λ matrix is more complicated, naturally, but Equation 3.12 still holds. (On the other hand, there is no real loss of generality in using Equation 3.11, since we are always free to *choose* parallel axes, and to align the x axis along the direction of v .)

Although the individual coordinates of an event change, in accordance with Equation 3.12, when we go from S to S' , there is a particular *combination* of them that remains the same (Problem 3.8):

$$I \equiv (x^0)^2 - (x^1)^2 - (x^2)^2 - (x^3)^2 = (x^{0'})^2 - (x^{1'})^2 - (x^{2'})^2 - (x^{3'})^2 \quad (3.13)$$

Such a quantity, which has the same value in any inertial system, is called an *invariant*. (In the same sense, the quantity $r^2 = x^2 + y^2 + z^2$ is invariant under rotations.) Now, I would like to write this invariant in the form of a sum: $\sum_{\mu=0}^3 x^{\mu} x^{\mu}$, but unfortunately there are those three irritating minus signs. To keep track of them, we introduce the *metric*, $g_{\mu\nu}$, whose components can be displayed as a matrix g :

$$g = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \quad (3.14)$$

* In an expression such as this the Greek letter used for the summation index, ν , is of course completely arbitrary. The same goes for the 'hanging' index μ , although it must match on the two sides of the equation. Thus Equation (3.12) could just as well be written $x^{\kappa'} = \Lambda_{\lambda}^{\kappa} x^{\lambda}$. Either expression stands for the set of four equations:

$$x^{0'} = \Lambda_0^0 x^0 + \Lambda_1^0 x^1 + \Lambda_2^0 x^2 + \Lambda_3^0 x^3$$

$$x^{1'} = \Lambda_0^1 x^0 + \Lambda_1^1 x^1 + \Lambda_2^1 x^2 + \Lambda_3^1 x^3$$

$$x^{2'} = \Lambda_0^2 x^0 + \Lambda_1^2 x^1 + \Lambda_2^2 x^2 + \Lambda_3^2 x^3$$

$$x^{3'} = \Lambda_0^3 x^0 + \Lambda_1^3 x^1 + \Lambda_2^3 x^2 + \Lambda_3^3 x^3$$

(i.e. $g_{00} = 1$; $g_{11} = g_{22} = g_{33} = -1$; all the rest are zero).^{*} With the help of $g_{\mu\nu}$, the invariant I can be written as a double sum:

$$I = \sum_{\mu=0}^3 \sum_{\nu=0}^3 g_{\mu\nu} x^\mu x^\nu = g_{\mu\nu} x^\mu x^\nu \quad (3.15)$$

Carrying things a step further, we define the *covariant* four-vector x_μ (index *down*) as follows:

$$x_\mu \equiv g_{\mu\nu} x^\nu \quad (3.16)$$

(i.e. $x_0 = x^0$, $x_1 = -x^1$, $x_2 = -x^2$, $x_3 = -x^3$). To emphasize the distinction we call the 'original' four-vector x^μ (index *up*) a *contravariant* four-vector. The invariant I can then be written in its cleanest form:

$$I = x_\mu x^\mu \quad (3.17)$$

(or, equivalently, $x^\mu x_\mu$). All this will no doubt seem like monstrous notational overkill, just to keep track of three pesky minus signs, but it's actually very simple, once you get used to it. (What's more, it generalizes nicely to non-Cartesian coordinate systems and to the curved spaces encountered in general relativity, though neither of these is relevant to us here.)

The position-time four-vector x^μ is the archetype for all *four-vectors*. We define a four-vector, a^μ , as a four-component object that transforms in the same way x^μ does when we go from one inertial system to another, to wit:

$$a^{\mu'} = \Lambda^{\mu'}_{\nu} a^\nu \quad (3.18)$$

with the same coefficients $\Lambda^{\mu'}_{\nu}$. To each such (contravariant) four-vector we associate a *covariant* four-vector a_μ , obtained by simply changing the signs of the spatial components, or, more formally

$$a_\mu = g_{\mu\nu} a^\nu \quad (3.19)$$

Of course, we can go back from covariant to contravariant by reversing the signs again:

$$a^\mu = g^{\mu\nu} a_\nu \quad (3.20)$$

where $g^{\mu\nu}$ are technically the elements in the matrix g^{-1} (however, since our metric is its own inverse, $g^{\mu\nu}$ is the same as $g_{\mu\nu}$). Given any two four-vectors, a^μ and b^μ , the quantity

$$a^\mu b_\mu = a_\mu b^\mu = a^0 b^0 - a^1 b^1 - a^2 b^2 - a^3 b^3 \quad (3.21)$$

^{*} I should warn you that some physicists define the metric with the opposite signs $(-1, 1, 1, 1)$. It doesn't *matter* much – if I is an invariant, so too is $-I$. But it does mean that you must be on the lookout for unfamiliar signs. Fortunately, most *particle* physicists nowadays use the convention in Equation 3.14.

is invariant (the same number in any inertial system). We shall refer to it as the *scalar product* of a and b ; it is the four-dimensional analog to the dot product of two three-vectors (there is no four-vector analog to the cross product).*

If you get tired of writing indices, feel free to use the dot notation:

$$a \cdot b \equiv a_\mu b^\mu \quad (3.22)$$

However, you will then need a way to distinguish this four-dimensional scalar product from the ordinary dot product of two three-vectors. The best way is to be scrupulously careful to put an arrow over all three-vectors (except perhaps the velocity, \mathbf{v} , which, since it is not part of a four-vector, is not subject to ambiguity). In this book, I use boldface for three-vectors. Thus

$$a \cdot b = a^0 b^0 - \mathbf{a} \cdot \mathbf{b} \quad (3.23)$$

We also use the notation a^2 for the scalar product of a^μ with itself.†

$$a^2 \equiv a \cdot a = (a^0)^2 - \mathbf{a}^2 \quad (3.24)$$

Notice, however, that a^2 need not be positive. Indeed, we can classify all four-vectors according to the sign of a^2 :

$$\begin{array}{ll} \text{If } a^2 > 0, & a^\mu \text{ is called } \textit{timelike} \\ \text{If } a^2 < 0, & a^\mu \text{ is called } \textit{spacelike} \\ \text{If } a^2 = 0, & a^\mu \text{ is called } \textit{lightlike} \end{array} \quad (3.25)$$

From *vectors* it is a short step to *tensors*: a second-rank tensor, $s^{\mu\nu}$, carries two indices, has $4^2 = 16$ components, and transforms with *two* factors of Λ :

$$s^{\mu\nu'} = \Lambda_\kappa^\mu \Lambda_\sigma^\nu s^{\kappa\sigma} \quad (3.26)$$

a third-rank tensor, $t^{\mu\nu\lambda}$, has three indices, $4^3 = 64$ components, and transforms with *three* factors of Λ :

$$t^{\mu\nu\lambda'} = \Lambda_\kappa^\mu \Lambda_\sigma^\nu \Lambda_\tau^\lambda t^{\kappa\sigma\tau} \quad (3.27)$$

* The closest thing is $(a^\mu b^\nu - a^\nu b^\mu)$, but this is a second-rank *tensor*, not a four-vector (see below).

† On its face, this is dangerously ambiguous notation, since a^2 could also be the second spatial component of a^μ . But in practice we so seldom refer to individual components that this causes no problems (if you really *mean* the component, better say so explicitly). More serious is the potential confusion

between a^2 and the square of the magnitude of the three-vector *part* of a^μ . I personally write the latter in bold face, to avoid any possible misunderstanding: $\mathbf{a}^2 \equiv \mathbf{a} \cdot \mathbf{a}$. This is not standard notation, however, and if you prefer some other device, that's fine. But I do urge you to find a clear way to distinguish a^2 from \mathbf{a}^2 , or you are asking for real trouble down the road.

and so on. In this hierarchy, a vector is a tensor of rank one, and a scalar (invariant) is a tensor of rank zero. We construct covariant and 'mixed' tensors by lowering indices (at the cost of a minus sign for each spatial index), for example

$$s^\mu{}_\nu = g_{\nu\lambda} s^{\mu\lambda}; \quad s_{\mu\nu} = g_{\mu\kappa} g_{\nu\lambda} s^{\kappa\lambda} \quad (3.28)$$

and so on. Notice that the product of two tensors is itself a tensor: $(a^\mu b^\nu)$ is a tensor of second rank; $(a^\mu t^{\nu\lambda\sigma})$ is a tensor of fourth rank; and so on. Finally, we can obtain from any tensor of rank $n + 2$ a 'contracted' tensor of rank n , by summing like upper and lower indices. Thus $s^\mu{}_\mu$ is a scalar; $t_\nu{}^{\mu\nu}$ is a vector; $a_\mu t^{\mu\nu\lambda}$ is a second-rank tensor.

3.3

Energy and Momentum

Suppose you're driving down the highway, and pretend for the sake of argument that you're going at close to the speed of light. You might want to keep an eye on two different 'times': if you're worried about making an appointment in San Francisco, you should check the stationary clocks posted now and then along the side of the road. But if you're wondering when would be an appropriate time to stop for a bite to eat, it would be more sensible to look at the watch on your wrist. For, according to relativity, the moving clock (in this case, your watch) is running slow (relative to the 'stationary' clocks on the ground), and so too is your heart rate, your metabolism, your speech and thought, *everything*. Specifically, while the 'ground' time advances by an infinitesimal amount dt , your own (or *proper*) time advances by the smaller amount $d\tau$:

$$d\tau = \frac{dt}{\gamma} \quad (3.29)$$

At normal driving speeds, of course, γ is so close to 1 that dt and $d\tau$ are essentially identical, but in elementary particle physics the distinction between laboratory time (read off the clock on the wall) and particle time (as it would appear on the particle's watch) is crucial. Although we can always get from one to the other, using Equation 3.29, in practice it is usually most convenient to work with proper time, *because τ is invariant* – all observers can read the particle's watch, and at any given moment they must all agree on what it says, even though their *own* clocks may differ from it and from one another.

When we speak of the 'velocity' of a particle (with respect to the laboratory), we mean, of course, the distance it travels (measured in the lab frame) divided by the time it takes (measured on the lab clock):

$$v = \frac{dx}{dt} \quad (3.30)$$

But in view of what has just been said, it is also useful to introduce the *proper velocity*, η , which is the distance traveled (again, measured in the lab frame) divided

by the proper time:*

$$\eta \equiv \frac{dx}{d\tau} \quad (3.31)$$

According to Equation 3.29, the two velocities are related by a factor of γ :

$$\eta = \gamma v \quad (3.32)$$

However, η is much easier to work with, for if we want to go from the lab system, S , to a moving system, S' , both the numerator and the denominator in Equation 3.30 must be transformed – leading to the cumbersome velocity addition rule Equation 3.5 – whereas in Equation 3.31 only the numerator transforms; $d\tau$, as we have seen, is invariant. In fact, proper velocity is part of a four-vector:

$$\eta^\mu = \frac{dx^\mu}{d\tau} \quad (3.33)$$

whose zeroth component is

$$\eta^0 = \frac{dx^0}{d\tau} = \frac{d(ct)}{(1/\gamma) dt} = \gamma c \quad (3.34)$$

Thus

$$\eta^\mu = \gamma(c, v_x, v_y, v_z) \quad (3.35)$$

Incidentally, $\eta_\mu \eta^\mu$ should be invariant, and it is:

$$\eta_\mu \eta^\mu = \gamma^2(c^2 - v_x^2 - v_y^2 - v_z^2) = \gamma^2 c^2 (1 - v^2/c^2) = c^2 \quad (3.36)$$

They don't make 'em more invariant than *that*!

Classically, momentum is mass times velocity. We would like to carry this over in relativity, but the question arises: which velocity should we use – *ordinary* velocity or *proper* velocity? Classical considerations offer no clue, for the two are equal in the nonrelativistic limit. In a sense, it's just a matter of definition, but there is a subtle and compelling reason why ordinary velocity would be a *bad* choice, whereas proper velocity is a *good* choice. The point is this: if we defined momentum as mv , then the law of conservation of momentum would be inconsistent with the principle of relativity (if it held in one inertial system, it would *not* hold in other inertial

* Proper velocity is a hybrid quantity, in the sense that distance is measured in the *lab* frame, whereas time is measured in the *particle* frame. Some people object to the adjective 'proper' in this context, holding that this should be reserved for quantities measured entirely in the particle frame. Of course, in its own frame the particle never moves at all –

its velocity is zero. If my terminology disturbs you, call η the 'four-velocity'. I should add that although proper velocity is the more convenient quantity to *calculate* with, ordinary velocity is still the more *natural* quantity from the point of view of an observer watching a particle fly past.

systems). But, if we define momentum as $m\eta$, then conservation of momentum is consistent with the principle of relativity (if it holds in one inertial system, it automatically holds in all inertial systems). I'll let you prove this for yourself in Problem 3.12. Mind you, this doesn't guarantee that momentum is conserved – that's a matter for *experiments* to decide. But it *does* say that if we're hoping to extend momentum conservation to the relativistic domain, we had better *not* define momentum as mv , whereas $m\eta$ is perfectly acceptable.

That's a tricky argument, and if you didn't follow it, try reading that last paragraph again. The upshot is that in relativity, momentum is defined as mass times *proper* velocity:

$$\mathbf{p} \equiv m\boldsymbol{\eta} \quad (3.37)$$

Since proper velocity is part of a four-vector, the same goes for momentum:

$$p^\mu = m\eta^\mu \quad (3.38)$$

The spatial components of p^μ constitute the (relativistic) momentum three-vector:

$$\mathbf{p} = \gamma m\mathbf{v} = \frac{m\mathbf{v}}{\sqrt{1 - v^2/c^2}} \quad (3.39)$$

Meanwhile, the 'temporal' component is

$$p^0 = \gamma mc \quad (3.40)$$

For reasons that will appear in a moment, we define the *relativistic energy*, E , as

$$E \equiv \gamma mc^2 = \frac{mc^2}{\sqrt{1 - v^2/c^2}} \quad (3.41)$$

The zeroth component of p^μ , then, is E/c . Thus, energy and momentum together make up a four-vector – the *energy-momentum four-vector* (or *four-momentum*)

$$p^\mu = \left(\frac{E}{c}, p_x, p_y, p_z \right) \quad (3.42)$$

Incidentally, from Equations 3.36 and 3.38 we have

$$p_\mu p^\mu = \frac{E^2}{c^2} - \mathbf{p}^2 = m^2 c^2 \quad (3.43)$$

which, again, is manifestly invariant.

The relativistic momentum (Equation 3.37) reduces to the classical expression in the nonrelativistic regime ($v \ll c$), but the same cannot be said for relativistic energy (Equation 3.41). To see how this quantity comes to be called 'energy,' we

expand the radical in a Taylor series:

$$E = mc^2 \left(1 + \frac{1}{2} \frac{v^2}{c^2} + \frac{3}{8} \frac{v^4}{c^4} + \dots \right) = mc^2 + \frac{1}{2} mv^2 + \frac{3}{8} m \frac{v^4}{c^2} + \dots \quad (3.44)$$

Notice that the *second* term here corresponds to the classical kinetic energy, while the leading term (mc^2) is a constant. Now you may recall that in classical mechanics only *changes* in energy are physically significant – you can add a constant with impunity. In this sense, the relativistic formula is consistent with the classical one, in the limit $v \ll c$ where the higher terms in the expansion are negligible. The constant term, which survives even when $v = 0$, is called the *rest energy*:

$$R \equiv mc^2 \quad (3.45)$$

the remainder, which is energy attributable to the motion of the particle, is the *relativistic kinetic energy*.*

$$T \equiv mc^2(\gamma - 1) = \frac{1}{2} mv^2 + \frac{3}{8} m \frac{v^4}{c^2} + \dots \quad (3.46)$$

In classical mechanics, there is no such thing as a massless particle; its momentum (mv) would be zero, its kinetic energy ($\frac{1}{2}mv^2$) would be zero, it could sustain no force, since $F = ma$, and hence (by Newton's third law) it could not exert a force on anything *else* – it would be a dynamical ghost. At first glance you might suppose that the same would be true in relativity, but a careful inspection of the formulas

$$\mathbf{p} = \frac{mv}{\sqrt{1 - v^2/c^2}}, \quad E = \frac{mc^2}{\sqrt{1 - v^2/c^2}} \quad (3.47)$$

reveals a loophole: when $m = 0$, the numerators are zero, but if $v = c$, the denominators *also* vanish, and these equations are indeterminate (0/0). So it is just possible that *we could allow* $m = 0$, *provided the particle always travels at the speed of light*. In this case, Equation 3.47 will not serve to define E and \mathbf{p} ; nevertheless, Equation 3.43 still holds:

$$v = c, \quad E = |\mathbf{p}|c \quad (\text{for massless particles}) \quad (3.48)$$

Personally, I would regard this 'argument' as a joke, were it not for the fact that massless particles (photons) are known to exist in nature, they *do* travel at the speed of light, and their energy and momentum *are* related by Equation 3.48. So we have

* Notice that I have never mentioned 'relativistic mass' in all this. It is a superfluous quantity that serves no useful function. In case you encounter it, the definition is $m_{rel} \equiv \gamma m$; it has died out because it differs from E only

by a factor of c^2 . Whatever can be said about m_{rel} could just as well be said about E . For instance, the 'conservation of relativistic mass' is nothing but conservation of *energy*, with a factor of c^2 divided out.

to take the loophole seriously. You may well ask: if Equation 3.47 doesn't define p and E , what *does* determine the momentum and energy of a massless particle? Not the mass (that's zero by assumption); not the speed (that's always c). How, then, *does* a photon with an energy of 2 eV differ from a photon with an energy of 3 eV? Relativity offers no answer to this question, but curiously enough *quantum mechanics does*, in the form of Planck's formula:

$$E = h\nu \quad (3.49)$$

It is the *frequency* of the photon that determines its energy and momentum: the 2-eV photon is *red*, and the 3-eV photon is *purple*!

3.4 Collisions

So far, relativistic energy and momentum are nothing but *definitions*; the *physics* resides in the empirical fact that these quantities are *conserved*. In relativity, as in classical mechanics, the cleanest application of the conservation laws is to *collisions*. Imagine first a classical collision, in which object A hits object B (perhaps they are both carts on an air table), producing objects C and D (Figure 3.2). Of course, C and D might be the same as A and B ; but we may as well allow that some paint (or whatever) rubs off A onto B , so that the final masses are not the same as the original ones. (We *do* assume, however, that A , B , C , and D are the only actors in the drama; if some wreckage, W , is left at the scene, then we would be talking about a more complicated process: $A + B \rightarrow C + D + W$.) By its nature, a collision is something that happens so fast that no *external* force, such as gravity, or friction with the track, has an appreciable influence. Classically, mass and momentum are always conserved in such a process; kinetic energy may or may not be conserved.

3.4.1 Classical Collisions

1. Mass is conserved: $m_A + m_B = m_C + m_D$.
2. Momentum is conserved: $\mathbf{p}_A + \mathbf{p}_B = \mathbf{p}_C + \mathbf{p}_D$.
3. Kinetic energy may or may not be conserved.

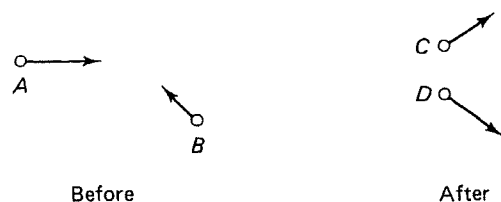


Fig. 3.2 A collision in which $A + B \rightarrow C + D$.

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I like to distinguish three types of collisions: 'sticky' ones, in which the kinetic energy *decreases* (typically, it is converted into heat); 'explosive' ones, in which the kinetic energy *increases* (for example, suppose A has a compressed spring on its front bumper, and the catch is released in the course of the collision so that spring energy is converted into kinetic energy); and *elastic* ones, in which the kinetic energy is conserved.

- (a) *Sticky* (kinetic energy decreases): $T_A + T_B > T_C + T_D$.
- (b) *Explosive* (kinetic energy increases): $T_A + T_B < T_C + T_D$.
- (c) *Elastic* (kinetic energy conserved): $T_A + T_B = T_C + T_D$.

In the extreme case of type (a), the two particles stick together, and there is really only *one* final object: $A + B \rightarrow C$. In the extreme case of type (b), a single object breaks in two: $A \rightarrow C + D$ (in the language of particle physics, A *decays* into C + D).

3.4.2

Relativistic Collisions

In a relativistic collision, *energy and momentum are always conserved*. In other words, all four components of the energy-momentum four-vector are conserved. As in the classical case, *kinetic* energy may or may not be conserved.

1. Energy is conserved: $E_A + E_B = E_C + E_D$.
2. Momentum is conserved: $\mathbf{p}_A + \mathbf{p}_B = \mathbf{p}_C + \mathbf{p}_D$.
3. Kinetic energy may or may not be conserved.

(The first two can be combined into a single expression: $p_A^\mu + p_B^\mu = p_C^\mu + p_D^\mu$.)

Again, we can classify collisions as sticky, explosive, or elastic, depending on whether the kinetic energy decreases, increases, or remains the same. Since the *total* energy (rest plus kinetic) is *always* conserved, it follows that rest energy (and hence also mass) increases in a sticky collision, decreases in an explosive collision, and is unchanged in an elastic collision.

- (a) *Sticky* (kinetic energy decreases): rest energy and mass increase.
- (b) *Explosive* (kinetic energy increases): rest energy and mass decrease.
- (c) *Elastic* (kinetic energy is conserved): rest energy and mass are conserved.

Please note: *except in elastic collisions, mass is not conserved*.* For example, in the decay $\pi^0 \rightarrow \gamma + \gamma$ the initial mass was $135 \text{ MeV}/c^2$, but the final mass is zero.

* In the old terminology, we would say that *relativistic* mass is conserved, but *rest* mass is not.

Here *rest* energy was converted into *kinetic* energy (or, in the absurd language of the popular press, infuriating to anyone with the slightest respect for dimensional consistency, 'mass was converted into energy'). Conversely, if mass is conserved, then the collision was elastic. In elementary particle physics, there is only one way this ever happens: the *same particles* come out as went in* – electron–proton scattering ($e + p \rightarrow e + p$), for example.

In spite of a certain structural similarity between the classical and relativistic analyses, there is a striking difference in the interpretation of inelastic collisions. In the classical case, we say that energy is converted from kinetic form to some 'internal' form (thermal energy, spring energy, etc.), or vice versa. In the relativistic analysis, we say that it goes from kinetic energy to *rest* energy or vice versa. How can these possibly be consistent? After all, relativistic mechanics is supposed to reduce to classical mechanics in the limit $v \ll c$. The answer is that all 'internal' forms of energy are reflected in the rest energy of an object. A hot potato *weighs more* than a cold potato; a compressed spring *weighs more* than a relaxed spring. On the macroscopic scale, rest energies are enormously greater than internal energies, so these mass differences are utterly negligible in everyday life, and very small even at the atomic level. Only in nuclear and particle physics are typical internal energies comparable to typical rest energies. Nevertheless, in principle, whenever you weigh an object, you are measuring not only the rest energies (masses) of its constituent parts, but all of their kinetic and interaction energies as well.

3.5

Examples and Applications

Solving problems in relativistic kinematics is as much an art as a science. Although the *physics* involved is minimal – nothing but conservation of energy and conservation of momentum – the *algebra* can be formidable. Whether a given problem takes two lines or seven pages depends a lot on how skillful and experienced you are at manipulating the tools and the tricks of the trade. I now propose to work a few examples, pointing out as I go along some of the labor-saving devices that are available to you [2].

Example 3.1 Two lumps of clay, each of mass m , collide head-on at $\frac{3}{5}c$ (Figure 3.3). They stick together. *Question:* What is the mass M of the final composite lump?

Solution: Conservation of energy says $E_1 + E_2 = E_M$. Conservation of momentum says $\mathbf{p}_1 + \mathbf{p}_2 = \mathbf{p}_M$. In this case, conservation of momentum is trivial: $\mathbf{p}_1 = -\mathbf{p}_2$, so the final lump is at rest (which was obvious from the start). The initial energies are

* In principle, if there existed two distinct pairs of particles (A, B and C, D) that happened to add up to the same total mass, then I suppose the reaction $A + B \rightarrow C + D$ might be considered 'elastic', but in reality there *are* no such coincidences, so to a particle physicist the word 'elastic' has come to *mean* that the same particles come out as went in.

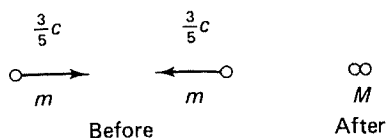


Fig. 3.3 Sticky collision of two equal masses (Example 3.1).

equal, so conservation of energy yields

$$Mc^2 = 2E_m = \frac{2mc^2}{\sqrt{1 - (3/5)^2}} = \frac{5}{4}(2mc^2)$$

Conclusion: $M = \frac{5}{2}m$. Notice that this is *greater* than the sum of the initial masses; in sticky collisions kinetic energy is converted into rest energy, so the mass increases. ■

Example 3.2 A particle of mass M , initially at rest, decays into two pieces, each of mass m (Figure 3.4). *Question:* What is the speed of each piece as it flies off?

Solution: This is, of course, the reverse of the process in Example 3.1. Conservation of momentum just says that the two lumps fly off in opposite directions at equal speeds. Conservation of energy requires that

$$M = \frac{2m}{\sqrt{1 - v^2/c^2}}, \quad \text{so} \quad v = c\sqrt{1 - (2m/M)^2}$$

This answer makes no sense unless M exceeds $2m$: there has to be at least enough rest energy available to cover the rest energies in the final state (any *extra* is fine; it can be soaked up in the form of kinetic energy). We say that $M = 2m$ is the *threshold* for the process $M \rightarrow 2m$ to occur. The deuteron, for example, is below the threshold for decay into proton plus neutron ($m_d = 1875.6 \text{ MeV}/c^2$; $m_p + m_n = 1877.9 \text{ MeV}/c^2$), and therefore is stable. A deuteron can be *pulled* apart, but only by pumping enough energy into the system to make up the difference. (If it puzzles you that a bound state of p and n should weigh *less* than the sum of its parts, the point is that the binding energy of the deuteron – which, like all internal energy, is reflected in its rest mass – is *negative*. Indeed, for *any* stable bound state the binding energy must be negative; if the composite particle weighs *more* than the sum of its constituents, it will spontaneously disintegrate.) ■

Example 3.3 A pion at rest decays into a muon plus a neutrino (Figure 3.5).

Question: What is the speed of the muon?

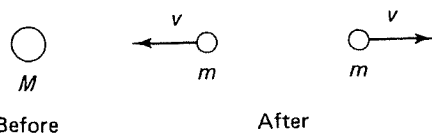


Fig. 3.4 A particle decays into two equal pieces. (Example 3.2).

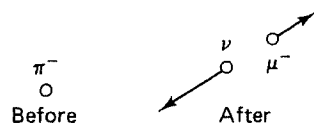


Fig. 3.5 Decay of the charged pion (Example 3.3).

Solution: Conservation of energy requires $E_\pi = E_\mu + E_\nu$. Conservation of momentum gives $\mathbf{p}_\pi = \mathbf{p}_\mu + \mathbf{p}_\nu$; but $\mathbf{p}_\pi = 0$, so $\mathbf{p}_\mu = -\mathbf{p}_\nu$. Thus the muon and the neutrino fly off back-to-back, with equal and opposite momenta. To proceed, we need a formula relating the energy of a particle to its momentum; Equation 3.43 does the job.*

Suggestion 1. To get the energy of a particle, when you know its momentum (or vice versa), use the invariant

$$E^2 - \mathbf{p}^2 c^2 = m^2 c^4 \quad (3.50)$$

In the present case, then:

$$\begin{aligned} E_\pi &= m_\pi c^2 \\ E_\mu &= c \sqrt{m_\mu^2 c^2 + \mathbf{p}_\mu^2} \\ E_\nu &= |\mathbf{p}_\nu| c = |\mathbf{p}_\mu| c \end{aligned}$$

Putting these into the equation for conservation of energy, we have

$$m_\pi c^2 = c \sqrt{m_\mu^2 c^2 + \mathbf{p}_\mu^2} + |\mathbf{p}_\mu| c$$

or

$$(m_\pi c - |\mathbf{p}_\mu|)^2 = m_\mu^2 c^2 + \mathbf{p}_\mu^2$$

Solving for $|\mathbf{p}_\mu|$,

$$|\mathbf{p}_\mu| = \frac{m_\pi^2 - m_\mu^2}{2m_\pi} c$$

Meanwhile, the energy of the muon (from Equation 3.50) is

$$E_\mu = \frac{m_\pi^2 + m_\mu^2}{2m_\pi} c^2$$

* You might be inclined to solve Equation 3.39 for the velocity, and plug the result into Equation 3.41, but that would be a very poor strategy. In general, velocity is a bad parameter to work with, in relativity. Better to use Equation 3.43, which takes you *directly* back and forth between E and \mathbf{p} .

Once we know the energy and momentum of a particle, it is easy to find its velocity. If $E = \gamma mc^2$ and $\mathbf{p} = \gamma m\mathbf{v}$, dividing gives

$$\mathbf{p}/E = \mathbf{v}/c^2$$

Suggestion 2. If you know the energy and momentum of a particle, and you want to determine its velocity, use

$$\mathbf{v} = \mathbf{p}c^2/E \quad (3.51)$$

So the answer to our problem is

$$v_\mu = \frac{m_\pi^2 - m_\mu^2}{m_\pi^2 + m_\mu^2} c$$

Putting in the actual masses, I get $v_\mu = 0.271c$.

There is nothing wrong with that calculation; it was a straightforward and systematic exploitation of the conservation laws. But I want to show you now a faster way to get the energy and momentum of the muon, by using four-vector notation. (I should put a superscript μ on all the four-vectors, but I don't want you to confuse the space-time index μ with the particle identifier μ , so here, and often in the future, I will suppress the space-time indices, and use a dot to indicate the scalar product.) Conservation of energy and momentum requires

$$p_\pi = p_\mu + p_\nu, \quad \text{or} \quad p_\nu = p_\pi - p_\mu$$

Taking the scalar product of each side with itself, we obtain

$$p_\nu^2 = p_\pi^2 + p_\mu^2 - 2p_\pi \cdot p_\mu$$

But

$$p_\nu^2 = 0; \quad p_\pi^2 = m_\pi^2 c^2, \quad p_\mu^2 = m_\mu^2 c^2; \quad \text{and} \quad p_\pi \cdot p_\mu = \frac{E_\pi}{c} \frac{E_\mu}{c} = m_\pi E_\mu$$

Therefore

$$0 = m_\pi^2 c^2 + m_\mu^2 c^2 - 2m_\pi E_\mu$$

from which E_μ follows immediately.

By the same token

$$p_\mu = p_\pi - p_\nu$$

Squaring yields

$$m_\mu^2 c^2 = m_\pi^2 c^2 - 2m_\pi E_\nu$$

But $E_v = |\mathbf{p}_v|c = |\mathbf{p}_\mu|c$, so

$$2m_\pi |\mathbf{p}_\mu| = (m_\pi^2 - m_\mu^2)c$$

which gives us $|\mathbf{p}_\mu|$. In this case, the problem was simple enough that the savings afforded by four-vector notation are meager, but in more complicated problems the benefits can be enormous.

Suggestion 3. Use four-vector notation, and exploit the invariant dot product. Remember that $p^2 = m^2c^2$ (Equation 3.43) for any (real) particle.

One reason why the use of invariants is so powerful in this business is that we are free to evaluate them in any inertial system we like. Frequently, the laboratory frame is not the simplest one to work with. In a typical scattering experiment, for instance, a beam of particles is fired at a stationary target. The reaction under study might be, say, $p + p \rightarrow$ whatever, but in the laboratory the situation is asymmetrical, since one proton is moving and the other is at rest. Kinematically, the process is much simpler when viewed from a system in which the two protons approach one another with equal speeds. We call this the *center-of-momentum* (CM) frame, because in this system the total (three-vector) momentum is zero.

Example 3.4 The Bevatron at Berkeley was built with the idea of producing antiprotons, by the reaction $p + p \rightarrow p + p + p + \bar{p}$. That is, a high-energy proton strikes a proton at rest, creating (in addition to the original particles) a proton-antiproton pair. *Question:* What is the threshold energy for this reaction (i.e. the minimum energy of the incident proton)?

Solution: In the laboratory the process looks like Figure 3.6a; in the CM frame, it looks like Figure 3.6b. Now, what is the condition for threshold? Answer: Just barely enough incident energy to create the two extra particles. In the lab frame, it is hard to see how we would formulate this condition, but in the CM it is easy: *all four final particles must be at rest*, with nothing 'wasted' in the form of kinetic energy. (We can't have that in the *lab* frame, of course, since conservation of momentum requires that there be some residual motion.)

Let p_{TOT}^μ be the *total* energy-momentum four-vector in the lab; it is conserved, so it doesn't matter whether we evaluate it before or after the collision. We'll do it *before*:

$$p_{\text{TOT}}^\mu = \left(\frac{E + mc^2}{c}, |\mathbf{p}|, 0, 0 \right)$$

where E and \mathbf{p} are the energy and momentum of the incident proton, and m is the proton mass. Let $p_{\text{TOT}}^{\mu'}$ be the total energy-momentum four-vector in the CM. Again, we can evaluate it before or after the collision; this time we'll do it *after*:

$$p_{\text{TOT}}^{\mu'} = (4mc, 0, 0, 0)$$

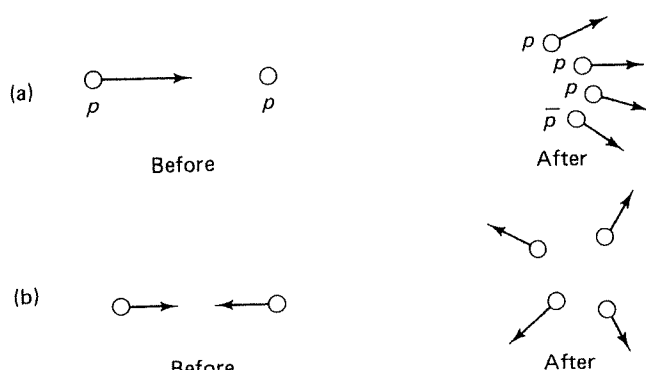


Fig. 3.6 $p + p \rightarrow p + p + p + \bar{p}$. (a) In the lab frame; (b) in the CM frame.

since (at threshold) all four particles are at rest. Now $p_{\text{TOT}}^{\mu} \neq p_{\text{TOT}}^{\mu'}$, obviously, but the invariant products $p_{\mu\text{TOT}}p_{\text{TOT}}^{\mu}$ and $p_{\mu\text{TOT}}'p_{\text{TOT}}^{\mu'}$ are equal:

$$\left(\frac{E}{c} + mc\right)^2 - p^2 = (4mc)^2$$

Using the standard invariant (Equation 3.50) to eliminate p^2 , and solving for E , we find

$$E = 7mc^2$$

Evidently, the incident proton must carry a kinetic energy at least six times its rest energy, for this process to occur. (And in fact the first antiprotons were discovered when the machine reached about 6000 MeV.)

This is perhaps a good place to emphasize the distinction between a *conserved* quantity and an *invariant* quantity. Energy is *conserved* – the same value *after* the collision as *before* – but it is not *invariant*. Mass is *invariant* – the same in all inertial systems – but it is not *conserved*. Some quantities are both invariant and conserved (e.g. electric charge); many are neither (speed, for instance). As Example 3.4 indicates, the clever exploitation of conserved and invariant quantities can save you a lot of messy algebra. It also demonstrates that some problems are easier to analyze in the CM system, whereas others may be simpler in the lab frame.

Suggestion 4. If a problem seems cumbersome in the lab frame, try analyzing it in the CM system.

Even if you're dealing with something more complicated than a collision of two identical particles, the CM (in which $\mathbf{p}_{\text{TOT}} = 0$) is still a useful reference frame, for in this system conservation of momentum is trivial: zero before, zero after. But you might wonder whether there is always a CM frame. In other words, given a swarm of particles with masses m_1, m_2, m_3, \dots , and velocities $\mathbf{v}_1, \mathbf{v}_2, \mathbf{v}_3, \dots$, does there necessarily exist an inertial system in which their total (three-vector) momentum

is zero? The answer is *yes*; I will prove it by finding the velocity of that frame and demonstrating that this velocity is less than c . The total energy and momentum in the lab frame (S) are

$$E_{\text{TOT}} = \sum_i \gamma_i m_i c^2; \quad \mathbf{p}_{\text{TOT}} = \sum_i \gamma_i m_i \mathbf{v}_i \quad (3.52)$$

Since p_{TOT}^μ is a four-vector, we can use the Lorentz transformations to get the momentum in system S' , moving in the direction of \mathbf{p}_{TOT} with speed v

$$|\mathbf{p}'_{\text{TOT}}| = \gamma \left(|\mathbf{p}_{\text{TOT}}| - \beta \frac{E_{\text{TOT}}}{c} \right)$$

In particular, this momentum is *zero* if v is chosen such that

$$\frac{v}{c} = \frac{|\mathbf{p}_{\text{TOT}}|c}{E_{\text{TOT}}} = \frac{|\sum \gamma_i m_i \mathbf{v}_i|}{\sum \gamma_i m_i c}$$

Now, the length of the sum of three-vectors cannot exceed the sum of their lengths (this geometrically evident fact is known as the *triangle inequality*), so

$$\frac{v}{c} \leq \frac{\sum \gamma_i m_i (v_i/c)}{\sum \gamma_i m_i}$$

and since $v_i < c$, we can be sure that $v < c$.* Thus the CM system always exists, and its velocity relative to the lab frame is given by

$$\mathbf{v}_{\text{CM}} = \frac{\mathbf{p}_{\text{TOT}} c^2}{E_{\text{TOT}}} \quad (3.53)$$

It seems odd, looking back at the answer to Example 3.4, that it takes an incident kinetic energy *six times* the proton rest energy to produce a p/\bar{p} pair. After all, we're only creating $2mc^2$ of new rest energy. This example illustrates the inefficiency of scattering off a stationary target; conservation of momentum forces you to waste a lot of energy as kinetic energy in the final state. Suppose we could have fired the two protons at one another, making the laboratory itself the CM system. Then it would suffice to give each proton a kinetic energy of only mc^2 , one-sixth of what the stationary-target experiment requires. This realization led, in the early 1970s, to the development of colliding-beam machines (see Figure 3.7). Today, virtually every new machine in high-energy physics is a collider.

Example 3.5 Suppose two identical particles, each with mass m and kinetic energy T , collide head-on. *Question:* What is their *relative* kinetic energy, T' (i.e. the kinetic energy of one in the rest system of the other)?

* I am tacitly assuming that at least one of the particles is massive. If *all* of them are massless, we may obtain $v = c$, in which case there is no CM system. For example, there is no CM frame for a single photon.



Fig. 3.7 Two experimental arrangements: (a) Colliding beams; (b) fixed target.

Solution: There are many ways to do this one. A quick method is to write down the total four-momentum in the CM and in the lab

$$p_{\text{TOT}}^\mu = \left(\frac{2E}{c}, 0 \right), \quad p_{\text{TOT}}^{\mu'} = \left(\frac{E' + mc^2}{c}, \mathbf{p}' \right)$$

set $(p_{\text{TOT}})^2 = (p_{\text{TOT}}')^2$:

$$\left(\frac{2E}{c} \right)^2 = \left(\frac{E' + mc^2}{c} \right)^2 - \mathbf{p}'^2$$

use Equation 3.50 to eliminate \mathbf{p}'

$$2E^2 = mc^2(E' + mc^2)$$

and express the answer in terms of $T = E - mc^2$ and $T' = E' - mc^2$

$$T' = 4T \left(1 + \frac{T}{2mc^2} \right) \quad (3.54)$$

The *classical* answer would have been $T' = 4T$, to which this reduces when $T \ll mc^2$. (In the rest system of B, A has, classically, twice the velocity, and hence four times as much kinetic energy, as in the CM.) Now, a factor of 4 is *some* benefit, to be sure, but the *relativistic* gain can be greater by far. Colliding electrons with a laboratory kinetic energy of 1 GeV, for example, would have a *relative* kinetic energy of 4000 GeV! ■

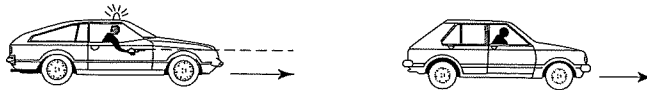
References

- 1 There are many excellent textbooks on special relativity. I especially recommend Smith, J. H. (1996) *Introduction to Special Relativity*, Dover, New York. For a fascinating (but unorthodox) approach, see (a) Taylor, E. F. and Wheeler, J. A. (1992) *Spacetime Physics*, 2nd edn. Freeman, San Francisco, C.A.
- 2 If you want to go into this much more deeply, the standard reference is Hagedorn, R. (1964) *Relativistic Kinematics*, Benjamin, New York.

Problems

- 3.1 Solve Equation 3.1 for x, y, z, t in terms of x', y', z', t' , and check that you recover Equation 3.3.
- 3.2 (a) Derive Equation 3.4.

- (b) According to clocks on the ground (system S), streetlights A and B (situated 4 km apart) were both turned on at precisely 8:00 P.M. Which one went on first according to an observer on a train (system S'), which moves from A toward B at $\frac{3}{5}$ the speed of light? How much later (in seconds) did the other light go on? *Note:* As always in relativity, we are talking here about what S' *observed*, *after* correcting for the time it took the light to reach her, *not* what she actually *saw* (which would depend on where she was located on the train).
- 3.3 (a) How do *volumes* transform? (If a container has volume V' in its own rest frame, S' , what is its volume as measured by an observer in S , with respect to which it is moving at speed v ?)
- (b) How do *densities* transform? (If a container holds ρ' molecules per unit volume in its own rest frame, S' , how many molecules per unit volume does it carry in S ?)
- 3.4 Cosmic ray muons are produced high in the atmosphere (at 8000 m, say) and travel toward the earth at very nearly the speed of light ($0.998c$, say).
- (a) Given the lifetime of the muon (2.2×10^{-6} sec), how far would it go before disintegrating, according to prerelativistic physics? Would the muons make it to ground level?
- (b) Now answer the same question using *relativistic* physics. (Because of time dilation, the muons last longer, so they travel farther.)
- (c) Pions are also produced in the upper atmosphere. In fact, the sequence is proton (from outer space) hits proton (in atmosphere) $\rightarrow p + p +$ pions. The pions then decay into muons: $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$; $\pi^+ \rightarrow \mu^+ + \nu_\mu$. But, the lifetime of the pion is much shorter (2.6×10^{-8} s). Assuming the pions have the same speed ($0.998c$), will they reach ground level?
- 3.5 Half the muons in a monoenergetic beam decay in the first 600 m. How fast are they going?
- 3.6 As the outlaws escape in their getaway car, which goes $\frac{3}{4}c$, the cop fires a bullet from the pursuit car, which only goes $\frac{1}{2}c$. The muzzle velocity (speed relative to gun) of the bullet is $\frac{1}{2}c$. Does the bullet reach its target?
- (a) According to prerelativistic physics?
- (b) According to relativity?



- 3.7 Find the matrix M that inverts Equation 3.12: $x^\mu = M^\mu_\nu x'^\nu$ (use Equation 3.3). Show that M is the matrix inverse of Λ : $\Lambda M = 1$.
- 3.8 Show that the quantity I (in Equation 3.13) is invariant under Lorentz transformations (Equation 3.8).
- 3.9 Given two four-vectors, $a^\mu = (3, 4, 1, 2)$ and $b^\mu = (5, 0, 3, 4)$, find: a_μ , b_μ , a^2 , b^2 , $a \cdot b$, a^2 , b^2 , and $a \cdot b$. Characterize a^μ and b^μ as timelike, spacelike, or lightlike.
- 3.10 A second-rank tensor is called *symmetric* if it is unchanged when you switch the indices ($s^{\mu\nu} = s^{\nu\mu}$); it is *antisymmetric* if it changes sign ($a^{\mu\nu} = -a^{\nu\mu}$).
- (a) How many independent elements are there in a symmetric tensor? (Since $s^{12} = s^{21}$, these would count as only *one* independent element.)
- (b) How many independent elements are there in an antisymmetric tensor?
- (c) Show that symmetry is preserved by Lorentz transformations – that is, if $s^{\mu\nu}$ is symmetric, so too is $s^{\mu'\nu'}$. What about *antisymmetry*?

- (d) If $s^{\mu\nu}$ is symmetric, show that $s_{\mu\nu}$ is also symmetric. If $a^{\mu\nu}$ is antisymmetric, show that $a_{\mu\nu}$ is antisymmetric.
- (e) If $s^{\mu\nu}$ is symmetric and $a^{\mu\nu}$ is antisymmetric, show that $s^{\mu\nu}a_{\mu\nu} = 0$.
- (f) Show that any second-rank tensor ($\mu^{\mu\nu}$) can be written as the sum of an antisymmetric part ($a^{\mu\nu}$) and a symmetric part ($s^{\mu\nu}$): $\mu^{\mu\nu} = a^{\mu\nu} + s^{\mu\nu}$. Construct $s^{\mu\nu}$ and $a^{\mu\nu}$ explicitly, given $\mu^{\mu\nu}$.
- 3.11 A particle is traveling at $\frac{3}{5}c$ in the x direction. Determine its proper velocity, η^μ (all four components).
- 3.12 Consider a collision in which particle A (with 4-momentum p_A^μ) hits particle B (4-momentum p_B^μ), producing particles C (p_C^μ) and D (p_D^μ). Assume the (relativistic) energy and momentum are conserved in systems S ($p_A^\mu + p_B^\mu = p_C^\mu + p_D^\mu$). Using the Lorentz transformations (Eq. 3.12), show that energy and momentum are also conserved in S' .
- 3.13 Is p^μ timelike, spacelike, or lightlike for a (real) particle of mass m ? How about a massless particle? How about a virtual particle?
- 3.14 How much more does a hot potato weigh than a cold one (in kg)?
- 3.15 A pion traveling at speed v decays into a muon and a neutrino, $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$. If the neutrino emerges at 90° to the original pion direction, at what angle does the μ come off? [Answer: $\tan \theta = (1 - m_\mu^2/m_\pi^2)/(2\beta\gamma^2)$.]
- 3.16 Particle A (energy E) hits particle B (at rest), producing particles C_1, C_2, \dots : $A + B \rightarrow C_1 + C_2 + \dots + C_n$. Calculate the threshold (i.e. minimum E) for this reaction, in terms of the various particle masses.

$$\left[\text{Answer: } \frac{M^2 - m_A^2 - m_B^2}{2m_B} c^2, \text{ where } M \equiv m_1 + m_2 + \dots + m_n \right]$$

- 3.17 Use the result of Problem 3.16 to find the threshold energies for the following reactions, assuming the target proton is stationary.*
- (a) $p + p \rightarrow p + p + \pi^0$
- (b) $p + p \rightarrow p + p + \pi^+ + \pi^-$
- (c) $\pi^- + p \rightarrow p + \bar{p} + n$
- (d) $\pi^- + p \rightarrow K^0 + \Sigma^0$
- (e) $p + p \rightarrow p + \Sigma^+ + K^0$
- 3.18 The first man-made Ω^- (Fig. 1.9) was created by firing a high-energy proton at a stationary hydrogen atom to produce a K^+/K^- pair: $p + p \rightarrow p + p + K^+ + K^-$; the K^- in turn hit another stationary proton, $K^- + p \rightarrow \Omega^- + K^0 + K^+$. What minimum kinetic energy is required (for the incident proton), to make an Ω^- in this way? (Gell-Mann must have done this calculation to see whether the experiment would be feasible.)

* Beware: The Particle Physics Booklet (and most other sources) list particle 'masses' in MeV. For example, the mass of the muon is quoted as 105.658 MeV. What they mean, of course, is the rest energy of the muon: $m_\mu c^2 = 105.658 \text{ MeV}$ – or, what is the same

thing, $m_\mu = 105.658 \text{ MeV}/c^2$. It is safest to convert formulas from mass to rest energy before plugging in any numbers. In this case, for example, multiply top and bottom by c^2 , to get $E_{\min} = [(Mc^2)^2 - (m_A c^2)^2 - (m_B c^2)^2]/2(m_B c^2)$.

3.19 Particle A, at rest, decays into particles B and C ($A \rightarrow B + C$).

(a) Find the energy of the outgoing particles, in terms of the various masses.

$$\left[\text{Answer: } E_B = \frac{m_A^2 + m_B^2 - m_C^2}{2m_A} c^2 \right]$$

(b) Find the magnitudes of the outgoing momenta.

$$\left[\begin{array}{l} \text{Answer: } |\mathbf{p}_B| = |\mathbf{p}_C| = \frac{\sqrt{\lambda(m_A^2, m_B^2, m_C^2)}}{2m_A c}, \\ \text{where } \lambda \text{ is the so-called } \textit{triangle function} : \\ \lambda(x, y, z) \equiv x^2 + y^2 + z^2 - 2xy - 2xz - 2yz. \end{array} \right]$$

(c) Note that λ factors: $\lambda(a^2, b^2, c^2) = (a+b+c)(a+b-c)(a-b+c)(a-b-c)$. Thus $|\mathbf{p}_B|$ goes to zero when $m_A = m_B + m_C$, and runs imaginary if $m_A < (m_B + m_C)$. Explain.

3.20 Use the result of Problem 3.19 to find the CM energy of each decay product in the following reactions (see footnote to Problem 3.17):

- (a) $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- (b) $\pi^0 \rightarrow \gamma + \gamma$
- (c) $K^+ \rightarrow \pi^+ + \pi^0$
- (d) $\Lambda \rightarrow p + \pi^-$
- (e) $\Omega^- \rightarrow \Lambda + K^-$

3.21 A pion at rest decays into a muon and a neutrino ($\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$). On the average, how far will the muon travel (in vacuum) before disintegrating? [Answer: $d = [(m_\pi^2 - m_\mu^2)/(2m_\pi m_\mu)]c\tau = 186 \text{ m.}$]

3.22 Particle A, at rest, decays into three or more particles: $A \rightarrow B + C + D + \dots$.

- (a) Determine the maximum and minimum energies that B can have in such a decay, in terms of the various masses.
- (b) Find the maximum and minimum electron energies in muon decay, $\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$.

3.23 (a) A particle traveling at speed u approaches an identical particle at rest. What is the speed (v) of each particle in the CM frame? (Classically, of course, it would just be $u/2$.)

$$[\text{Answer: } (c^2/u) (1 - \sqrt{1 - u^2/c^2})]$$

(b) Find $\gamma \equiv 1/\sqrt{1 - v^2/c^2}$ in terms of $\gamma' \equiv 1/\sqrt{1 - u^2/c^2}$.

$$[\text{Answer: } \sqrt{(\gamma' + 1)/2}]$$

(c) Use your result in part (b) to express the kinetic energy of each particle in the CM frame, and thus re-derive Equation 3.54

3.24 In reactions of the type $A + B \rightarrow A + C_1 + C_2 + \dots$ (in which particle A scatters off particle B, producing C_1, C_2, \dots), there is another inertial frame, in addition to the lab (B at rest) and the CM ($\mathbf{p}_{TOT} = 0$), which is sometimes useful. It is called the *Breit*, or 'brick wall' frame, and it is the system in which A recoils with its momentum reversed ($\mathbf{p}_{after} = -\mathbf{p}_{before}$), as though it had bounced off a brick wall. Take the case of elastic scattering ($A + B \rightarrow A + B$); if particle A carries energy E , and scatters at an angle θ , in the CM, what is its energy in the Breit frame? Find the velocity of the Breit frame (magnitude and direction) relative to the CM.

- 3.25 In a two-body scattering event, $A + B \rightarrow C + D$, it is convenient to introduce the Mandelstam variables

$$s \equiv (p_A + p_B)^2/c^2$$

$$t \equiv (p_A - p_C)^2/c^2$$

$$u \equiv (p_A - p_D)^2/c^2$$

- (a) Show that $s + t + u = m_A^2 + m_B^2 + m_C^2 + m_D^2$.

The *theoretical* virtue of the Mandelstam variables is that they are Lorentz invariants, with the same value in any inertial system. *Experimentally*, though, the more accessible parameters are energies and scattering angles.

- (b) Find the CM energy of A , in terms of s , t , u and the masses. [Answer: $E_A^{\text{CM}} = (s + m_A^2 - m_B^2)c^2/2\sqrt{s}$.]

- (c) Find the Lab (B at rest) energy of A . [Answer: $E_A^{\text{lab}} = (s - m_A^2 - m_B^2)c^2/2m_B$.]

- (d) Find the total CM energy ($E_{\text{TOT}} = E_A + E_B = E_C + E_D$). [Answer: $E_{\text{TOT}}^{\text{CM}} = \sqrt{s}c^2$.]

- 3.26 For elastic scattering of identical particles, $A + A \rightarrow A + A$, show that the Mandelstam variables (Problem 3.25) become

$$s = 4(p^2 + m^2c^2)/c^2$$

$$t = -2p^2(1 - \cos \theta)/c^2$$

$$u = -2p^2(1 + \cos \theta)/c^2$$

where p is the CM momentum of the incident particle, and θ is the scattering angle.

- 3.27 Work out the kinematics of Compton scattering: a photon of wavelength λ collides elastically with a charged particle of mass m . If the photon scatters at angle θ , find its outgoing wavelength, λ' . [Answer: $\lambda' = \lambda + (h/mc)(1 - \cos \theta)$.]