14.8: Negative Energies and Antiparticles

Figure $14.8.5$ illustrates another oddity in the role of intermediary particles in collisions. In the unprimed frame, particle C appears to be emitted by particle A and absorbed by particle B. In the primed frame the reverse is true; it appears to be emitted by B and absorbed by A. These judgements are based on the fact that the A vertex occurs earlier than the B vertex in the unprimed frame, while the B vertex occurs earlier in the primed frame. However, since these distinctions are based on time ordering in different reference frames of events separated by a spacelike interval, they are inherently not relativistically invariant. Since the principle of relativity states that physical laws are the same in all inertial reference frames, we have a conceptual problem to overcome.

A related problem has to do with the computation of energy from mass and momentum. The solution of equation $E^2 = p^2c^2 + m^2c^4$ for the energy has a sign ambiguity that we have so far ignored:

$$E = \pm\left(p^2c^2 + m^2c^4\right)^{1/2} \tag{14.8.1}$$

A natural tendency would be to omit the minus sign and just consider positive energies. However, this would be a mistake — experience with quantum mechanics indicates that **both** solutions must be considered.

Richard Feynman won the Nobel Prize in physics largely for developing a consistent interpretation of the above negative energy solutions, which we now relate. Notice that the four-momentum points backward in time in a spacetime diagram if the energy is negative. Feynman suggested that a particle with four-momentum $\underline{p}$ is equivalent to the corresponding antiparticle with four-momentum $-\underline{p}$. Thus, we interpret a particle with momentum **p** and energy E < 0 as an antiparticle with momentum **-p** and energy -E > 0.

Antiparticles are known to exist for all particles. If a particle and its antiparticle meet, they can annihilate, creating one or more other particles. Correspondingly, if energy is provided in the right form, a particle-antiparticle pair can be created.

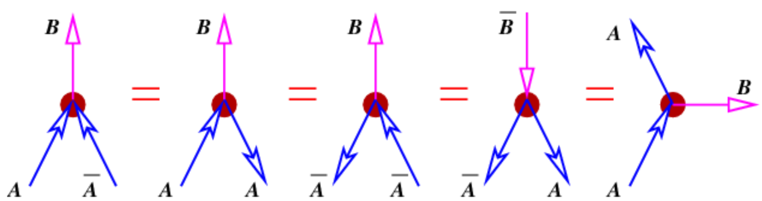

Figure 14.8.6:: Equivalence of different processes according to Feynman's picture.

Suppose a particular kind of particle, call it an A particle, produces a B particle when it annihilates with its antiparticle $\bar{A}$. This is illustrated in the left panel in Figure $14.8.6$. In Feynman's view, this process is equivalent to the scattering of an A particle backward in time by a B particle, the scattering of an $\bar{A}$ backward in time by a B particle, the creation of an $\bar{A}A$ pair moving backward in time by a $\bar{B}$ particle (an antiB), and the emission of a B particle by an A particle moving forward in time.

The statement "moving backward in time" has stimulated generations of physics students to contemplate the possibility that Feynman's picture makes time travel possible. As far as we know, this is not so. The key phrase is equivalent to. In other words, causality still works forward in time as we have come to expect.

The real utility of the "backward in time" picture is that it makes calculations easier, since processes which are normally thought of as being very different turn out to have the same mathematical form.

Returning to the ambiguity shown in Figure $14.8.5$, it turns out that it does not matter whether the picture in the left or right panel is chosen. According to the Feynman view the two processes are equivalent if one small correction is made — if the intermediary particle going from left to right is a C particle, then the intermediary particle going from right to left in the other picture is a $\bar{C}$ particle, or an antiC. It is immaterial whether the arrow representing either the C or the $\bar{C}$ points forward or backward in time. The key point is that if an arrow points into a vertex, the four-momentum of that particle contributes to the input side of the momentum-energy budget for that vertex. If an arrow points away from a vertex, then the four-momentum contributes to the output side.