Additional Example

EXAMPLE 32–5 **Energy and momentum are conserved.** In addition to the "number" conservation laws which help explain the decay schemes of particles, we can also apply the laws of conservation of energy and momentum. The decay of a Σ^+ particle at rest with a rest mass of $1189\,\mathrm{MeV}/c^2$ (Table 32–2 in the next Section) commonly yields a proton (rest mass of $938\,\mathrm{MeV}/c^2$) and a neutral pion, π^0 (rest mass of $135\,\mathrm{MeV}/c^2$):

$$\Sigma^+ \rightarrow \mathrm{p} + \pi^0.$$

What are the kinetic energies of the decay products, assuming the Σ^+ parent particle was at rest?

APPROACH We find the energy release from the change in mass $(E = mc^2)$ as we did for nuclear processes (Eq. 30–2 or 31–1), and apply conservation of energy and momentum.

SOLUTION The energy released, or Q-value, is the change in mass times c^2:

$$Q = \left[m_{\Sigma^+} - (m_\mathrm{p} + m_{\pi^0})\right]c^2 = \left[1189 - (938 + 135)\right]\mathrm{MeV} = 116\,\mathrm{MeV}.$$

This energy Q becomes the kinetic energy of the resulting decay particles, p and π^0:

$$Q = \mathrm{KE}_\mathrm{p} + \mathrm{KE}_{\pi^0}$$

with each particle's kinetic energy related to its momentum by (Eqs. 26–7 and 26–10):

$$\mathrm{KE}_\mathrm{p} = E_\mathrm{p} - m_\mathrm{p}c^2 = \sqrt{(p_\mathrm{p}c)^2 + (m_\mathrm{p}c^2)^2} - m_\mathrm{p}c^2,$$

and similarly for the pion. From momentum conservation, the proton and pion have the same magnitude of momentum since the original particle was at rest: $p_\mathrm{p} = p_{\pi^0} = p.$ Then

$$Q = 116\,\mathrm{MeV} = \left[\sqrt{(pc)^2 + (938\,\mathrm{MeV})^2} - 938\,\mathrm{MeV}\right] + \left[\sqrt{(pc)^2 + (135\,\mathrm{MeV})^2} - 135\,\mathrm{MeV}\right].$$

We solved this for pc, which gives $pc = 189\,\mathrm{MeV}$. Substituting into the expression for the kinetic energy, first for the proton, then for the pion we obtain $\mathrm{KE}_\mathrm{p} = 19\,\mathrm{MeV}$ and $\mathrm{KE}_{\pi^0} = 97\,\mathrm{MeV}$.

32–5 Neutrinos—Recent Results

The study of neutrinos is a "hot" subject today. Experiments are being carried out in deep underground laboratories, sometimes in deep mine shafts. The thick layer of earth above is meant to filter out all other "background" particles, leaving mainly the very weakly interacting neutrinos to arrive at the detectors.

Two very important results have come to the fore in our young twenty-first century. One result is that the three neutrinos, ν_e, ν_μ, ν_τ, can occasionally change into one another in certain circumstances, a phenomenon called

Neutrino oscillations

neutrino flavor oscillation (each of the three types being called, whimsically, a different "flavor"). This result suggests that the lepton numbers L_e, L_μ, and L_τ are not perfectly conserved. But the sum, $L_\mathrm{e} + L_\mu + L_\tau$, is believed to be always conserved.

The second exceptional result has long been speculated on: are neutrinos massless as originally thought, or do they have a nonzero rest mass? Rough upper limits on the masses have been made. But in 2002, astrophysical experiments showed that the sum of all three neutrino masses must be less than about $1\,\mathrm{eV}/c^2$. But can the masses be zero? Not if there are the flavor oscillations discussed above. It seems likely that at least one neutrino type has rest mass of at least 0.05 eV, a remarkable result.