Freeze-Out in the Early Universe

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To understand the particle physics/cosmological term “freeze-out”, one needs to understand two things first.

1. Mean free path, and
2. Interaction dependence on ambient temperature (energy level of particles interacting).

1 Mean Free Path

The “mean free path” is the average distance an incoming particle (“beam particle” in the lab) travels in a medium before interacting with a particle in that medium (“target particle” in the lab). The formula for calculating it is derived in Volume 2 of Student Friendly QFT, pgs. 365-366. We will not repeat the derivation here, but provide some intuitive justification for why it works.

1.1 Understanding a Quantity Used in the Mean Free Path Formula

The expression for mean free path includes, as one of its factors, the cross section.

The cross-section σ is a measure of the probability that a given type of a single incoming particle will interact with a given single target particle, of given type. The classical world cross section of an object (like an apple or a pumpkin) on a target range is directly related to the probability of a shooter hitting that target. Larger cross section perpendicular to the bullet trajectory means higher probability of a hit; smaller cross-section, a lower probability. The same concept is adopted for particle physics scattering. Higher σ means higher probability of two particles interacting, i.e., having a collision. (For the math behind it all, see Volume 1 of SFQFT, Chap. 17 beginning on pg. 432.)

The units of cross-section are what one would expect, area units, typically cm^2. An electron interacting with another electron would have a different cross section than an electron interacting with a neutrino. Each set of two different types of particles has its own particular numeric value for cross-section.

1.2 The Formula

The mean free path can be determined numerically, for any incoming particle and a given target medium, by knowing the cross section and the particle number density of the target medium n_t. The relation is

$$\text{average distance traveled before collision} = \text{mean free path} = \frac{1}{\sigma n_t}. \tag{1}$$

1.3 Getting a Feeling for the Formula

Note that if the particle number density n_t is higher, we would expect the incoming particle to be more likely to interact (collide) with some particle in the medium. More particles = more chances of collision. And that means a shorter path before collision occurs. This is reflected in (1).

If the cross-section σ is higher, the probability of interaction is also higher, so we would expect interaction to occur sooner, i.e., the mean free path would be shorter. Again, this is reflected in (1).

For units, cross-section is typically cm^2, particle number density is cm^{-3} (particle number has no units), so the mean free path has units of cm. It all hangs together.

2 Interaction Direction Dependence on Particle Energy

Note that if energy is high, such that the mass of every particle in the interaction is negligible compared to that energy level, it is essentially equally easy to produce heavier particles as it is lighter particles.

For example, for electron-positron and tau-antitau annihilation and creation, with interaction energy level much higher than the mass of the tau, there is equal likelihood of electron-positron annihilation resulting in a tau and anti-tau, as there is for tau and anti-tau annihilation resulting in an electron and positron. There is plenty of ambient kinetic energy available kicking up incoming electron/positron pair energy to well above what is needed to convert that energy to two tau masses. See Fig. 1.

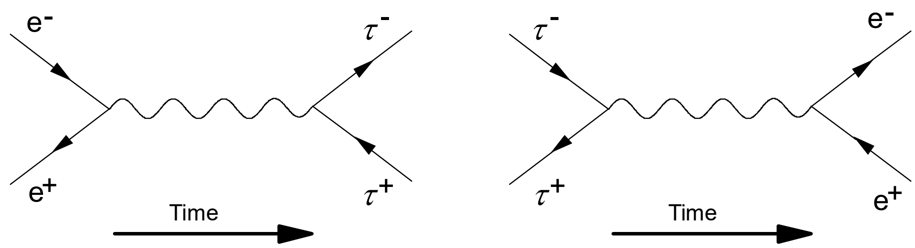

Figure 1. E >> $2m_\tau$ Equal Probability of Interaction in Either Direction

In a mixture of particles at high energy (like just after the Big Bang) we would find equal numbers of taus (plus anti-taus) as electrons (plus anti-electrons). This would be an equilibrium condition.

But consider what happens when temperature falls such that the average particle in the mixture has energy less than that of a tau. Then the left-hand interaction in Fig. 1 cannot happen. There is not enough energy to create taus. But, the tau mass is much greater than the electron mass, so no matter what the ambient temperature, taus can always produce electrons and positrons.

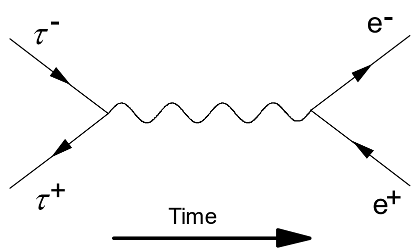

Figure 2. E < $2m_\tau$ Interaction Only in This Direction

So, as the universe cooled, we would come to a point where taus are nowhere to be found, but electrons and positrons would be common. We are no longer in equilibrium. The interaction cannot proceed both ways.

This could be considered "freeze-out", as the taus are precipitated out as temperature drops. But the term is more commonly applied when some of the heavier particles, for reasons to be discussed below, actually remain. This is not the case for taus, but it may be for dark matter, as we will see.

3 Energy Level, Density, and Interactions

Consider a situation where, instead of taus in Figs. 1 and 2, we had more exotic particles, such as dark matter particles. And take into consideration the mean-free path relation (1).

We would have the situation like that of Fig. 1 in the very early stage of the universe, i.e., equal amounts of normal matter and dark matter. Each could create the other, the reaction would go in both directions, and the particles would be in equilibrium.

As temperature falls, the reaction tends more and more to go in only one direction, from the heavier DM particles to the lighter, normal matter, ones. So, we go out of equilibrium, and get more and more normal matter, and less and less DM. One might expect this to go on until there were no DM left, but (1) kicks in and changes that scenario.

As the temperature drops in the early universe, the density also drops due to expansion. We get to a point where DM particle density n_t gets very low, so the mean free path (1) for any one particle to hit any other gets very long. It gets so long, in fact, that DM particles and antiparticles have trouble finding one another, so their interactions effectively cease. At this point, the number of DM particles is essentially "frozen". They will no longer annihilate, at any appreciable number, to reduce their total number in the universe.

The amount that gets frozen out depends on how long the DM particles were close enough to interact, after the temperature decreased below equilibrium levels. This, of course, can be calculated, but doing so is not trivial. A longer time of higher density means fewer DM particles today. A shorter time of high density means more DM left over now.

If DM particles are quite heavy, even though their number would be less than the number of normal matter particles they annihilate into, they could constitute the 85% or so of all matter (mass-wise, not number-wise) we observe.

This is the “freeze-out” mechanism of astrophysics.

4 Other Considerations

The prior explication implies DM will not decay on its own into normal matter particles. If it could, all DM would have long turned into normal matter. DM could, of course, decay into other type DM particles and still be DM.

Perhaps DM can decay into normal matter particles, but the mediating particle is so heavy that, in the present universe, it effectively does not act, and there is no such decay of any significant level.

Further, the mediating boson in Figs. 1 and 2, with DM replacing taus, is generally not considered to be a photon (unless micro charged DM is a reality), but some other, typically heavy, typically unknown, mediator. In that case, the interaction could be shut down when temperature falls below the level where such a boson could be created from the energy available. That would also be a contributing factor in how much DM freezes out.

Finally, we have ignored the imbalance between matter and antimatter in order to keep things simple. No one knows for sure how that imbalance arose, or whether the imbalance arose before or after any speculated DM freeze-out. The freeze-out principle works effectively the same way in either case.