

Are Progenies of Thermalized Systems Always Thermal?

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We examine the extent to which the products of in-medium reactions in a thermalized system can be regarded as either thermally or chemically equilibrated. Our results can be used to advantage at the decoupling stages of observable particles in cosmology, astrophysics, and relativistic heavy-ion collisions. The basic idea is to compare the various moments of the energy spectrum of the products to those of an ideal thermal system of the products characterized by the appropriate temperature T and chemical potential μ . Under arbitrary conditions of degeneracy and relativity, a reliable calculation of all the moments of even ideal fermions or bosons is cumbersome, unless special numerical techniques are employed. We therefore focus on the first and second moments, and take suitable ratios to characterize the degree of non-thermality. Much physical insight can be gained even at this level.

The non-thermality of the emerging products, which we take to leave the system without further interactions, can arise, for example, from (1) the nature of the transition amplitudes which can favor specific regions of energies and momenta, (2) energy or momentum thresholds, and (3) spectral modifications caused by in-medium effects. Examples include reactions such as (1) $\nu_i + \bar{\nu}_i \rightarrow \nu_j + \bar{\nu}_j$, (i and j refer to any of the e , μ , and τ flavors), $\gamma^* \rightarrow \nu_i + \bar{\nu}_i$, $e^+ + \gamma^* \rightarrow e^+ + \nu_i + \bar{\nu}_i$, $e^- + e^- \rightarrow e^- + e^- + \nu_i + \bar{\nu}_i$, etc., in astrophysical situations, and (2) $\rho \rightarrow \pi^+ + \pi^-$, $\Delta \rightarrow n + \pi$, etc., in heavy-ion collisions. Specifically, we compute the dimensionless ratio

$$\zeta(\mu, T) = \frac{\mathcal{E} / \Gamma}{(\mathcal{E} / \Gamma)^2},$$

where \mathcal{E} is the energy released per unit volume per unit time, \mathcal{E}^2 is the squared energy per unit volume per unit time, and Γ is the rate or number of reactions per unit volume per unit time, by taking into full account the effects of the transition amplitudes and 4-momentum conservation. This ratio is contrasted with the ideal gas benchmark ratio

$$\zeta_{th}(\mu, T) = \frac{\langle E^2 \rangle_{th} / n}{(\langle E \rangle_{th} / n)^2},$$

where the symbol $\langle \dots \rangle_{th}$ indicates the thermal convolutions without regard to transition amplitudes and 4-momentum conservation, and n is the number density of the thermalized products. Our exact numerical results for both cases are discussed in conjunction with analytical results in limiting situations of degeneracy and relativity in order to provide both qualitative and, where possible, quantitative understandings of the select examples studied. This study was supported in part by a URECA fellowship, and by NSF Grant No. Phy-02043935.