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Causal Equation of State of Hadron Resonance Gas with Relativistic Excluded Volumes and Its Relation to Morphological Thermodynamics

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Here we present a solution to the long-standing problem of constructing the causal equation of state of hadron resonance gas model (HRGM) with Lorentz contracted eigenvolumes of particles with the hard-core repulsion. It is based on the concept of Induced Surface and Curvature Tension (ISCT) [1] to treat the excluded volumes of hard spheres in the high-pressure region. Its mathematically sound and extensive derivation is obtained according to principles of morphological thermodynamics [2]. Practically an exact formula for the relativistic second virial coefficient (excluded volume) is obtained and investigated for various equations of state and a wide range of temperatures T and is shown that it reproduces a close packing of equal spheres limit $v_{exc} = 1-\pi/(3\sqrt{2}) \approx 0.26$ in case of high temperatures with sufficient accuracy without any prior knowledge about such system configuration. We as well propose an ansatz to take into account the effect of Lorentz contraction for higher-order virial coefficients of Boltzmann particles with hard-core repulsion. Such an ansatz allows us to obtain the expected vanishing limit for the effective relativistic excluded volume for high temperatures $T \gg m$. The proposed relativistic ISCT equation of state is applied to hadron mixtures to obtain a temperature dependence of the speed of sound c_S for nucleons, pions, and light hadrons. It is shown that consideration of Lorentz contraction of only the second virial coefficient does not lead to a fully causal equation of state, since the speed of sound exceeds the speed of light by about 10%, but the inclusion of relativistic contraction of higher-order virial coefficients makes the ISCT equation of state causal on a wide range of temperatures even far above the temperatures of hadrons existence.
References:
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