

# Thermal instability, evaporation and thermodynamics of one-dimensional liquids in weakly-interacting Bose-Bose mixtures

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We study the low-temperature thermodynamics of weakly-interacting uniform liquids in one-dimensional attractive Bose-Bose mixtures. The Bogoliubov approach is used to simultaneously describe quantum and thermal fluctuations. First, we investigate in detail two different thermal mechanisms driving the liquid-to-gas transition, the dynamical instability and the evaporation, and we draw the phase diagram. Then, we compute the main thermodynamic quantities of the liquid, such as the chemical potential, the Tan's contact, the adiabatic sound velocity and the specific heat at constant volume. The strong dependence of the thermodynamic quantities on the temperature may be used as a precise temperature probe for experiments on quantum liquids.

## I. INTRODUCTION

Fluids are traditionally classified as gases or liquids depending on the possibility of being self-bound. Gases have a positive pressure, so that in absence of a confining container these expand until they occupy the whole available space. Liquids are normally much denser than gases and have an equilibrium density fixed by the zero-pressure condition, or, equivalently, by minimizing the free-energy per particle [1]. The equilibrium density is obtained balancing a long-distance attraction (typically of van der Waals type) and a short-range repulsion. Liquids are therefore self-bound, and the uniform state can easily break down to form small droplets. As the temperature is raised, the thermal contribution to the kinetic energy plays against the attractive interactions and makes a liquid less self-bound. Once a critical temperature is reached, the liquid evaporates into a gas.

Quantum effects play a key role at very low temperatures, where the quantum contribution to the kinetic energy is significant. While most liquids solidify upon cooling at atmospheric pressure, helium remains liquid even at absolute zero temperature due to the large zero-point motion caused by its small atomic mass. Understanding the quantum properties of liquid helium is challenging, because it is a dense system with strong interactions, so that perturbative theories cannot be directly applied and a careful modeling of the short-range details of the potential is needed [2–8].

A novel and very different class of quantum liquids emerged in recent studies with ultracold atomic gases [9, 10]. Ultracold dilute liquids have been experimentally created and investigated in three-dimensional (3D) samples with anisotropic dipolar interactions [11–18] and in Bose-Bose mixtures with isotropic contact interactions [19–21]. These liquids exhibit exceptionally low densities (eight orders of magnitude lower than helium's) and temperatures (nine orders of magnitude lower than the freezing point of most classical liquids). Ultracold droplets can be accurately described by microscopic models which are much simpler than the ones

needed for liquid helium. In fact, droplets are formed in the weakly-interacting regime, so that perturbative theories can be used. An ultradilute liquid forms when the interaction strengths are tuned in such a way that the dominant contribution to the energy (the mean-field part) is close to vanishing. Under these conditions, the importance of beyond-mean-field quantum fluctuations (which are usually subleading) is greatly enhanced, and these can provide the balancing mechanism needed to obtain a liquid. Quantum droplets are therefore stable due to genuine many-body effects. Such liquids have a number of advantages as there is an exquisite experimental control over interactions, temperature, spatial dimension, trapping, and relative populations in mixtures. As such, they can model other complex and very different many-body systems, including liquid helium. The evaporation leads to the reduction of the number of particles in the liquid as discussed for the zero temperature case in Refs. [19, 22, 23], although it cannot be clearly distinguished from three-body losses in current experiments [20, 21].

These quantum liquids have been predicted to exist also in one-dimensional (1D) Bose-Bose mixtures [24–26], where beyond-mean-field effects are greatly enhanced, and three-body collisions strongly reduced [27, 28]. A 1D configuration should therefore allow for a more precise characterization of the evaporation process. First experiments with quantum droplets in confined geometries have been recently reported [29]. Differently from the three-dimensional case, the stability of 1D liquids requires a net mean-field repulsion which competes with an effective attraction provided by quantum fluctuations [24]. One-dimensional liquids generated a significant interest, and recent works explored their zero temperature phase diagram [25] and dynamics [30–32].

However, the experiments are inherently performed at finite temperature [20, 29], and an important open problem is the understanding of thermal effects in quantum liquids. These systems in particular require novel temperature probes [9], because the standard technique for thermometry in ultracold gases (time-of-flight expansion) cannot obviously be applied to self-bound systems. One should therefore resort to *in-situ* techniques, such as the ones exploited in recent ultracold-gas experiments to measure with high-precision several thermodynamic quantities. These include the sound velocity, the free energy, the specific heat at constant volume, the Tan's contact

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# Thermodynamics Of Thermal Instability

**Josiah Willard Gibbs**



## **Thermodynamics Of Thermal Instability:**

**The Thermodynamics of thermal instability in liquids** Subrahmanyam Chandrasekhar,1959      **Methods in Protein Structure and Stability Analysis: Conformational stability, size, shape, and surface of protein molecules** Vladimir N. Uversky,2007 Protein research is a frontier field in science Proteins are widely distributed in plants and animals and are the principal constituents of the protoplasm of all cells and consist essentially of combinations of a amino acids in peptide linkages Twenty different amino acids are commonly found in proteins and serve as enzymes structural elements hormones immunoglobulins etc and are involved throughout the body and in photosynthesis This book gathers new leading edge research from throughout the world in this exciting and exploding field of research      *Thermal Instability in a Spherical Region Heated from Below* Michael Sherman,Ivan Catton,1967 The classical Rayleigh thermal stability problem of an infinite horizontal fluid layer heated from below is extended to the case of a fluid confined within a rigid sphere whose wall is nonuniformly heated The temperature distribution on the wall is specified so that a constant temperature gradient is established in the direction of the body force acting on the fluid heated from below Two different variational principles are presented each equivalent to the eigenvalue problem for the critical Rayleigh number the stability criterion These principles form the basis for two approximate methods of determining upper bounds to the critical Rayleigh number The critical Rayleigh number obtained is 16 132 based on a unit diameter which is almost ten times greater than that of the horizontal layer configuration based on a unit height The results are compared with a previously published analysis and are found to be 10 percent lower Author      **Fluid Dynamics in Physics, Engineering and Environmental Applications** Jaime Klapp,Abraham Medina,Anne Cros,Carlos A. Vargas,2012-10-13 The book contains invited lectures and selected contributions presented at the Enzo Levi and XVII Annual Meeting of the Fluid Dynamic Division of the Mexican Physical Society in 2011 It is aimed to fourth year undergraduate and graduate students and scientists in the field of physics engineering and chemistry that have interest in Fluid Dynamics from the experimental and theoretical point of view The invited lectures are introductory and avoid the use of complicate mathematics The other selected contributions are also adequate to fourth year undergraduate and graduate students The Fluid Dynamics applications include multiphase flow convection diffusion heat transfer rheology granular material viscous flow porous media flow geophysics and astrophysics The material contained in the book includes recent advances in experimental and theoretical fluid dynamics and is adequate for both teaching and research      *Stability of Thermodynamic Systems* J. Casas-Vazques,G. Lebon,1982-07      **New Ideas Concerning Black Holes and the Universe** Eugene Tatum,2020 The ideas presented in this book are new scientific theories based largely upon a spate of very recent astronomical observations These theories include a cosmological model that appears to be superior in many respects to the inflationary concordance model proposed thermal stability criteria for a generic quantum black hole theoretical constraints concerning black hole binary graviton emissions theoretical effects of abelian vortices on

space time and a proposed solution to the mystery of the observed asymmetry between universal matter and antimatter The new ideas presented in this book have been selected in order to inspire others that regardless of the impending limits of observation the scientific creative process will continue **NASA Thesaurus** ,1994 **The Collected Works of J.**

**Willard Gibbs: Thermodynamics** Josiah Willard Gibbs,1928 The Thermodynamics of Rotating Disks Francisco Valdes,1980 Magnetic Fields in Diffuse Media Alexander Lazarian,Elisabete M. de Gouveia Dal Pino,Claudio Melioli,2014-11-14 This volume presents the current knowledge of magnetic fields in diffuse astrophysical media Starting with an overview of 21st century instrumentation to observe astrophysical magnetic fields the chapters cover observational techniques origin of magnetic fields magnetic turbulence basic processes in magnetized fluids the role of magnetic fields for cosmic rays in the interstellar medium and for star formation Written by a group of leading experts the book represents an excellent overview of the field Nonspecialists will find sufficient background to enter the field and be able to appreciate the state of the art *Thermodynamics* Josiah Willard Gibbs,1928 *Modern Thermodynamics* Dilip K. Kondepudi,Dilip Kondepudi,Ilya Prigogine,1998-08-18 Thermodynamics is a core part of most science and engineering curricula However most texts that are currently available to students still treat thermodynamics very much as it was presented in the 19th century generally for historical rather than pedagogical reasons Modern Thermodynamics takes a different approach and deals with the relationship between irreversible processes and entropy The relationship between irreversible processes and entropy is introduced early on enabling the reader to benefit from seeing the relationship in such processes as heat conduction and chemical reactions This text presents thermodynamics in a contemporary and exciting manner with a wide range of applications and many exercises and examples Students are also encouraged to use computers through the provision of Mathematica code and Internet WWW addresses where real data and additional information can be found FEATURES A truly modern approach to thermodynamics presenting it as a science of irreversible processes whilst avoiding dividing the subject into equilibrium and non equilibrium thermodynamics An extensive range of applications drawn from science and engineering along with many real world examples and exercises Written by two well known authors of whom Professor Ilya Prigogine was awarded the Nobel Prize for his research into thermodynamics CONTENTS Part I Historical Roots From Heat Engines to Cosmology Basic Concepts First Law of Thermodynamics Second Law of Thermodynamics and the Arrow of Time Entropy in the Realm of Chemical Reactions Part II Equilibrium Thermodynamics Extremum Principles and General Thermodynamic Relations Basic Thermodynamics of Gases Liquids and Solids Thermodynamics of Phase Change Thermodynamics of Solutions Thermodynamics of Chemical Transformations Fields and Internal Degrees of Freedom Thermodynamics of Radiation Part III Fluctuations and Stability The Gibbs Theory of Stability Critical Phenomena and Configurational Heat Capacity Theory of Stability and Fluctuations Based on Entropy Production Part IV Linear Nonequilibrium Thermodynamics Nonequilibrium Thermodynamics The Foundations Nonequilibrium Thermodynamics The

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Nonlinear Thermodynamics Dissipative Structures Postface Where do we go from here     **Experimental Thermodynamics  
of Non-reacting Fluids** Bernard Le Neindre, Boris Vodar, 1975     **Thermodynamic Inequalities in Gases and  
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two approximate methods are developed for calculating upper bounds to the critical Rayleigh number It is found that the  
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analyses Author     **NBS Special Publication** ,1968     **Ceramic Abstracts** ,1930

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