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Volume 54

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IN MEMORIAM
HERBERT WALTHER (1935–2006)

It is with great sadness that the Editors report the passing of Professor Herbert Walther on July 22, 2006. Professor Walther expanded the horizons of our understanding of the interaction of radiation with matter. The physics community will sorely miss his presence. Professor Walther assumed co-editorship of the *Advances* series starting with Volume 33 and continued in that role through Volume 51, which was a special issue, edited by Henry Stroke, to honor his co-editor Benjamin Bederson. Volume 53, edited by Gerhard Rempe and Marlan Scully, was published as a tribute to Professor Walther.

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PREFACE

Volume 54 of the *Advances* Series contains ten contributions, covering a diversity of subject areas in atomic, molecular and optical physics. The chapter by Regal and Jin reviews the properties of a Fermi degenerate gas of cold potassium atoms in the crossover regime between the Bose–Einstein condensation of molecules and the condensation of fermionic atom pairs. The transition between the two regions can be probed by varying an external magnetic field. Sherson, Julsgaard, and Polzik explore the manner in which light and atoms can be entangled, with applications to quantum information processing and communication. They report on the result of recent experiments involving the state entanglement of distant ensembles and a method for storing the quantum state of an optical field in an atomic ensemble. Recent developments in cold Rydberg atom physics are reviewed in the chapter by Choi, Knuffman, Cubel Liebisch, Reinhard, and Raithel. Fascinating experiments are described in which cold, highly excited atoms ("Rydberg" atoms) and cold plasmas are generated. Evidence for a collective excitation of Rydberg matter is also presented. Griffin and Pindzola offer an account of non-perturbative quantal methods for electron–atom scattering processes. Included in the discussion are the R-matrix with pseudo-states method and the time-dependent close-coupling method. An extensive review of the R-matrix theory of atomic, molecular, and optical processes is given by Burke, Noble, and Burke. They present a systematic development of the R-matrix method and its applications to various processes such as electron–atom scattering, atomic photoionization, electron–molecule scattering, positron–atom scattering, and atomic/molecular multiphoton processes. Electron impact excitation of rare-gas atoms from both their ground and metastable states is discussed in the chapter by Boffard, Jung, Anderson, and Lin. Excitation cross sections measured by the optical method are reviewed with emphasis on the physical interpretation in terms of electronic structure of the target atoms. Ozier and Moazzen-Ahmadi explore internal rotation of symmetric top molecules. Developments of new experimental methods based on high-resolution torsional, vibrational, and molecular beam spectroscopy allow accurate determination of internal barriers for these symmetric molecules. The subject of attosecond and angstrom science is reviewed by Niikura and Corkum. The underlying physical mechanisms allowing one to generate attosecond radiation pulses are described and the technology needed for the preparation of such pulses is discussed. Le Gouët, Bretenaker, and Lorgeré describe how rare earth ions embedded in crystals can be used for processing optically carried broadband radio-frequency signals. Methods for reaching tens of gigahertz instantaneous bandwidth with submegahertz resolution using such devices are analyzed in detail and demonstrated experimentally. Finally, in the chapter by Illing, Gauthier, and Roy, it is shown that small perturbations applied to optical systems can be used to suppress or control optical chaos, spatio-temporal dynamics, and patterns. Applications of these techniques to communications, laser stabilization, and improving the sensitivity of low-light optical switches are explored.

The Editors would like to thank all the contributing authors for their contributions and for their cooperation in assembling this volume. They would also like to express their appreciation to Dr. Anita Koch at Elsevier for her invaluable assistance.

Ennio Arimondo Paul Berman Chun Lin

Contents

Cold Rydberg Atoms

J.-H. Choi, B. Knuffman, T. Cubel Liebisch, A. Reinhard and G. Raithel

Non-Perturbative Quantal Methods for Electron–Atom Scattering Processes

D.C. Griffin and M.S. Pindzola

R-Matrix Theory of Atomic, Molecular and Optical Processes

P.G. Burke, C.J. Noble and V.M. Burke

Electron-Impact Excitation of Rare-Gas Atoms from the Ground Level and Metastable Levels

John B. Boffard, R.O. Jung, L.W. Anderson and C.C. Lin

Internal Rotation in Symmetric Tops

I. Ozier and N. Moazzen-Ahmadi

Attosecond and Angstrom Science

Hiromichi Niikura and P.B. Corkum

Atomic Processing of Optically Carried RF Signals

Jean-Louis Le Gouët, Fabien Bretenaker and Ivan Lorgeré

EXPERIMENTAL REALIZATION OF THE BCS-BEC CROSSOVER WITH A FERMI GAS OF ATOMS

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Abstract

Ultracold atomic gases have proven to be remarkable model systems for exploring quantum mechanical phenomena. Experimental work on gases of fermionic atoms in particular has seen astounding recent progress. In the short span of time between 2001 and 2004 accessible Fermi gas systems evolved from normal Fermi liquids at moderate temperatures to superfluids in the BCS-BEC crossover. This was made possible by unique control over interparticle interactions using Feshbach resonances in ^{6}Li and ^{40}K gases. In this chapter we present the story of the experimental realization of BCS-BEC crossover physics from the point of view of studies using ^{40}K at JILA. We start with some historical context and an introduction to the theory of the BCS-BEC crossover and Feshbach resonances. We then present studies of a normal ^{40}K Fermi gas at a Feshbach resonance and the work required to cool the gas to temperatures where superfluidity in the crossover is predicted. These studies culminated in the first observation of a phase transition in the BCS-BEC crossover regime, a task accomplished through detection of condensation of fermionic atom pairs. We also discuss subsequent work that confirmed the crossover nature of the pairs in these condensates.

1. Introduction

1.1. Historical Perspective

The phenomenon of superconductivity/superfluidity has fascinated and occupied physicists since the beginning of the 20th century. In 1911 superconductivity was discovered when the resistance of mercury was observed to go to zero below a critical temperature (Onnes, 1911). Although liquid ^{4}He was actually used in this discovery, the superfluid phase of liquid ^{4}He was not revealed until the 1930s when the viscosity of the liquid below the λ point (2.17 K) was measured (Allen and Misener, 1938; Kapitza, 1938). Much later, ^{3}He, the fermionic helium isotope, was also found to be superfluid at yet a much colder temperature than ^{4}He

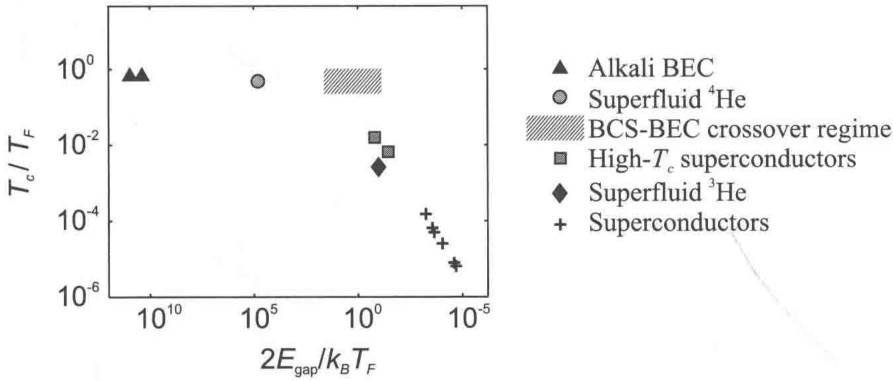

FIG. 1. Classic experimental realizations of superfluidity/superconductivity arranged according to the binding energy (twice the excitation gap, E_{gap}) of the constituent fermions. The vertical axis shows the corresponding transition temperature, T_c, to a superfluid/superconducting state compared to the Fermi temperature, T_F. (Figure reproduced with permission from Ref. (Holland et al., 2001).)

(Osheroff et al., 1972). Relatively recently in 1986, high-temperature superconductors in Copper-oxide materials further enlarged the list of superconducting materials (Bednorz and Mueller, 1986).

These "super" systems, which we will refer to in general as superfluids, are listed in Fig. 1, but they are only classic examples. There are many other physical systems that display superfluid properties from astrophysical phenomena such as neutron stars, to excitons in semiconductors, to atomic nuclei (Snoke and Baym, 1995). Although the physical properties of these systems vary widely, they are all linked by their counterintuitive behaviors such as frictionless flow and quantized vorticity. The manifestation of these effects depends upon, for example, whether the system in question is electrically charged (superconductors) or neutral (superfluids). Besides these intriguing properties, there are many practical reasons for the intense research in this field; arguably the most useful super-systems are superconductors, and if a robust room-temperature superconductor were created it would be an amazing discovery.

Some of the first attempts to understand the phenomenon of superfluidity were in the context of Bose–Einstein condensation (BEC) of an ensemble of bosonic particles (Randeria, 1995). BEC is a consequence of the quantum statistics of bosons, which are particles with integer spin, and it results in a macroscopic occupation of a single quantum state (Fig. 2) (Bose, 1924; Einstein, 1925). Fritz London proposed in 1938 that superfluid ^{4}He was a consequence of Bose–Einstein condensation of bosonic ^{4}He (London, 1938). (^{4}He behaves as a boson because it is made up of an even number of $1/2$ integer spin fermions—electrons, protons, and neutrons.) Physicists such as Blatt et al. pushed a similar idea in the context of superconductors in proposing that "at low temper-