TRENDS IN THEORETICAL PHYSICS
Volume I

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EDITED BY

P.J. Ellis
and
Y.C. Tang

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Preface

The Theoretical Physics Institute was established at the School of Physics and Astronomy of the University of Minnesota in January of 1987. As part of the program of the Institute, a colloquium series on Trends in Theoretical Physics was started in the Fall of 1988. Distinguished speakers were invited here to give colloquia on a wide range of topics in theoretical physics. These colloquia were very well received by the audience. Consequently, it was decided to collect manuscripts from the speakers and publish a book for wide circulation. In making this decision, we were also influenced by the fact that there seems to be no journal which deals with the whole field of theoretical physics at a level accessible to the non-specialist.

The topics are entirely the choice of the speakers. Our only request to them was that the talk should represent an overview of the topic, supplemented by their personal viewpoints and physical insights. As will be evident to the reader, a number of the speakers have been able to provide a more detailed written account than was possible in a one-hour colloquium. It is our hope that the book will be useful to all members of the physics community, experimentalists and theorists alike.

Since it is our feeling that physics should not be overly compartmentalized into subfields, we have not grouped the manuscripts in this way. We hope that the random order will assist in the cross-fertilization of ideas among subfields, which is so beneficial in understanding how nature works. Of course, many topics in theoretical physics could not be covered in this volume, but we plan to fill in some of the gaps with a second volume next year.

We would like to express our gratitude to many people; first, of course, to the speakers themselves and second, to our colleagues in the School of Physics and Astronomy. Among the latter, we especially wish to mention S. Gasiorowicz and L. McLerran for their encouragement to proceed with the idea of publishing the book, and J. Broadhurst for his technical assistance with the text editing system LaTeX used to produce this volume. We also thank Lori McWilliam Pickert (Archetype Publishing Inc.) for her invaluable help with the Addison-Wesley sei style. Several of the manuscripts were typed by Sandy Smith and we thank her for cheerfully carrying out this task. Last, but certainly not least, we acknowledge our gratitude to Allan Wylde for agreeing to publish this book and for the assistance that he and others at Addison-Wesley have provided in this endeavor.

P. J. Ellis
Y. C. Tang

University of Minnesota
August 1989

Foreword

The formal announcement, on January 28, 1987, of the creation of a new Theoretical Physics Institute at the University of Minnesota, revealed very little of how the Institute came into being. The story really began more than four decades ago, when William I. Fine first got excited about physics when reading the *World Book Encyclopedias.* Although his career took him through legal work as assistant district attorney in Dallas, Texas, judge advocate trial lawyer for the U.S.A.F. and a private attorney to real estate development, his interest in physics continued, and his reading in the field kept him well abreast of the advances of the last two decades. We first met at a party in the early 80's, and soon got past the usual chit-chat about quarks and the "large picture" in the unification of all forces. I found Bill Fine extremely well-informed about what was going on in a variety of areas in physics, so it was a pleasure to get together from time to time and talk about the field. On one occasion Bill asked me how a committed layman could contribute to physics. After some conversations we came up with the idea of starting a Theoretical Physics Institute. From that moment on, Bill's devotion to the project never flagged, even when the response of potential corporate donors was very discouraging. I recall consoling ourselves with the thought that things could be worse, as described by an anecdote told by a friend who visited a major university. At a party following his colloquium, he met a visiting Japanese scholar, who turned out to be a Chaucer specialist. When asked whether there was much interest in Chaucer in Japan, he answered, "none whatsoever, just like here".

In 1985 I introduced Bill to Gloria Lubkin, editor of *Physics Today*, who became a very involved and essential advisor and resource for the project, and is now on the steering board. It was she who led us to broaden our concept from a narrow concentration on particle physics, and it was she who suggested that Leo Kadanoff be brought in as advisor and consultant.

This group of people, together with Allen Goldman, Charles Campbell, then Head of the School of Physics and Astronomy at the University of Minnesota, and Marvin Marshak, current Head of the School began working on involving the university in a more massive way than was originally contemplated. President Kenneth Keller of the University of Minnesota agreed to match an outside fund both for the creation of two chairs in Theoretical Physics, and with a significant budget line permanent fund. It was Bill Fine who provided the outside funding necessary to trigger the creation of the TPI, and it is his remarkable generosity that is responsible for the existence of the TPI.

Several years ago a friend lent me a book of essays and reviews written by Ludwig Boltzmann. One of the essays entitled "Journey to Eldorado" described his visit to the University of California at Berkeley in 1905. One of the experiences that he remarked on was visiting Stanford University, which had been endowed by Leland Stanford's widow. Boltzmann writes how remarkable that seemed to him; at home, he said, he would have expected the founding of a hospice for abandoned kittens. The tradition of private funds being used to create centers of learning, be they universities, libraries, telescopes or institutes is an old one in the United States, but it is not always that it is rooted in the passionate interest of an individual in a field so far removed from practical pay-offs. Bill Fine continues to be deeply involved in all aspects of the activities of TPI. I hope that he is having fun getting to talk with a remarkable group of visitors, among whom are the authors of the articles in this volume. He and they share a curiosity and a devotion to understanding how the universe ticks.

Stephen Gasiorowicz
University of Minnesota
August, 1989

Dedicated to William I. Fine
in appreciation of his central role
in the establishment of the
Theoretical Physics Institute
at the University of Minnesota.

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La Grande Illusion: Aspects of the Non-Relativistic Description of the Three–Nucleon System

F. S. Levin
Physics Department
Brown University
Providence, Rhode Island 02912

Although a complete understanding of the three-nucleon system has not been attained, much has been accomplished: this system is rich in experimental and theoretical achievements. This chapter reviews a selected set of experimental data and the successes and failures of the non-relativistic, nucleons-only, quantal description of them. Instances are noted where relativistic effects must be included. The review is intended to be accessible by the non-expert, so that the treatment of material is qualitative with the stress on gaining a physical understanding of the phenomena. Many surprising theoretical results have been discovered over the years by researchers studying the three- nucleon system and a number of them are described. Included among these are: the need for a theoretical framework such as the Faddeev equations; the Efimov effect; the influence of the non-measurable, deuteron D-state probability; the non-existence of the conventionally-defined, proton-deuteron scattering length; the phenomenon of scaling; the failure, in the proton-deuteron case, of a standard approximation used in analyses of charged-projectile collisions with nuclei; the apparent failure of the method of stationary phase and nonetheless its apparent utility in describing breakup collisions; and the successful use of two-body dynamics to explain phenomena that previously only the very complicated, Faddeev-type of three-body dynamics could account for.

1.1 Introduction

This review is written mainly for the non–expert in the area of few–nucleon physics. Its stress is on qualitative aspects of both the few nucleon systems and the theoretical frameworks used to describe them. An important feature in this regard is a discussion of how well data are fitted (and sometimes how well they are measured); this includes comments on the nature of the assumptions that go into the theoretical calculations. An equally important feature is a recounting of some of the theoretical surprises that have been encountered in the almost three-decades of analyses based on Faddeev-type equations. Indeed, the failure of textbook scattering theory and the introduction of the Faddeev equations themselves can be considered the first surprise in the area of three–particle theory. These surprises as well as the current set of large and small failures to fit data combine to make this corner of physics a fascinating, frustrating and piquant area of research to report on.

Not all topics in few nucleon physics are treated herein, hence the eclectic nature of this review: it is a biased sampling, with the particular topics chosen to illustrate some of what was understood in early 1989 about few–nucleon observables and why the theory has been so delightful a theater in which to work. The framework chosen for this review has two components: non–relativistic quantum mechanics and the assumption that a description in terms of neutrons and protons is adequate. One aim of the review will be to assess not only the appropriateness of these two components but whether such a description is illusory and why. Another will be to convey to the non–specialist a sense of why research in this area is as exciting and alive as in any other.

Although neutrons and protons are assumed to be the basic constituents, it is often useful to regard them as two different charge states of a more fundamental constituent, the nucleon (spin 1/2, mass equal to an atomic mass unit, etc.). There are then two well studied versions of the three–*nucleon* system: one consists of two neutrons and a proton, denoted *nnp*; the other contains two protons and a neutron, denoted *ppn* [1]. Of the pairs that can be formed from the preceding triplets, only the neutron–proton system can exist in a particle–stable bound state, viz, the deuteron, $^2H \equiv d = (n+p)$. The bound tri-nucleons $^3H = (n+n+p)$ and $^3He = (p+p+n)$ are then the least complex nuclei after the deuteron.

Since ^{3}H and ^{3}He have no bound excited states, then all the tri-nucleon excited states are in the continuum. For *nnp* they are of two forms: either $n+d$ or $n+n+p$. Similarly, the continuum states of the *ppn* system are $p+d$ and $p+p+n$. Note that n+d and p+d always refer to a free nucleon and the ground state of the deuteron, since the latter nucleus also has no particle–stable excited states.

Three–nucleon continuum states occur in nuclear reactions, for example:

$$\begin{aligned} n+d &\rightarrow n+d \\ &\rightarrow n+n+p, \end{aligned}$$

and also in processes involving non–hadronic probes:

$$\begin{aligned} \gamma+{}^3He &\rightarrow p+d \\ &\rightarrow p+p+n, \end{aligned}$$

or

$$e+{}^3H \rightarrow e+n+n+p.$$

In contrast to the last process, *elastic* electron scattering is a means of investigating electromagnetic properties of the tri-nucleon *bound* states.

The three–nucleon system has long been studied, and a great deal is known about it, both experimentally and theoretically. A major theoretical breakthrough occurred in the 1960's, when Faddeev–type theories of three–particle collisions were successfully used to interpret experimental data [2], even though in order to circumvent then computational difficulties most of these early analyses were based on simplified and/or unrealistic forms of the nucleon–nucleon interaction or their corresponding transition operators (defined in Sec. 1.2 below). More recently the efforts of many workers have finally led to fully realistic interactions being employed in calculations. These latter calculations are highly non–trivial, and it was believed for some time that only through such complex three–body dynamics could the three nucleon system be understood. It has very recently become apparent, however, that at least for the lower energies and, to date, excluding three–particle (breakup) continuum states, one can use *two–body* dynamics to understand important features of this system.

This generally unexpected progression from complex to simpler dynamics is one of the most recent examples of a variety of surprising and stimulating theoretical developments in this field. A number of them will be chronicled in this review of selected aspects of the three–nucleon system. As noted in the preceding, a major emphasis will be on the successes and failures of the non–relativistic, nucleons–only description. Pions (and other mesons) are thus not considered to be active ingredients in the three–nucleon system, although they will enter the description indirectly, for example, in meson exchange current contributions to electromagnetic processes. Furthermore, they are fundamental in modern formulations of the nucleon–nucleon interaction. By suppressing the mesonic degrees of freedom, the nucleons–only description is thus one involving effective inter-