DUAL RESONANCE MODELS AND SUPERSTRINGS

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Paul H Frampton

University of North Carolina at Chapel Hill

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PREFACE TO REPRINTED AND EXPANDED EDITION

The development of string and superstring theories has an interesting history mainly because the periods of intense research activity 1968–74 and 1984– are separated by some ten years during which only a small number of papers were published. "Dual Resonance Models" was the only book on dual models and strings published during the first period. Shortly after its publication, the bottom dropped out of the field. The book went out of print in 1979, by which time interest in the subject had waned.

The main reason for reprinting the 1974 text of "Dual Resonance Models" is the widespread resurgence of interest in string theories. The book provides a comprehensive set of references for the period 1968–74 and, beyond that, many of the ideas and techniques are still germane in present superstring theories. A Supplement on superstrings, together with a small set of reprinted papers, has been added; hence the new title, "Dual Resonance Models and Superstrings." In the reprinted text from "Dual Resonance Models," typographical errors have been corrected and references updated.

As a digression, my first intimation that something unexpected had occurred in string theory (after ten years) came while visiting CERN, Switzerland, in August 1984, when Lars Brink told me from Michael Green and John Schwarz, who were then at the Aspen Center for

Physics, Colorado, that $O(32)$ is anomaly free for open superstrings. This message was conveyed to me because just four months earlier I had stated at the ICTP in Trieste, Italy, that all open superstrings were potentially anomalous; Green and Schwarz had been in the audience. Now they had discovered the elegant mechanism by which $O(32)$ uniquely escapes the fatal difficulty of chiral anomalies.

The construction of the $E(8) \times E(8)$ heterotic string by David Gross and his collaborators at Princeton University gave a more geometrical scheme for introduction of Yang-Mills symmetry than the unsatisfying multiplicative Chan-Paton factor of old. These developments compelled the scientific community to take seriously the idea of a superstring as a "theory of everything." Firstly, it is a real candidate for a consistent model of quantum gravity; the theory not only can describe gravity but actually requires that gravity must exist. Second, by compactification to four spacetime dimensions one can hope to make contact with the gauge field theories which successfully describe strong and electroweak interactions at experimentally accessible energies.

Of course, there is room for skepticism. Superstrings have no basis in, or even motivation from, experiment. Further, superstrings seem to have been discovered by historical accident and therefore may be just one of many possible consistent frameworks for quantum gravity. Certainly experiment, and not just mathematical consistency, is the ultimate test of any physical theory. Nevertheless, it is when one makes detailed calculations in superstring theory that one is constantly impressed by the remarkable properties which emerge. Superstrings could provide at least an existence theorem for a finite quantum gravity unified with gauge field theory.

The abrupt 1974 demise of dual resonance models for strong interactions was foreseeable because an alternative approach, gauge field theory, had been potentially available for almost twenty years. An

equally abrupt demise of superstrings would require an alternative, better approach to quantum gravity. At present, to my knowledge, a plausible competitor to the superstring is nowhere in sight. At this time, therefore, the superstring is expected to remain of interest to physicists for several years; it seems likely that it will take that long to establish any meaningful confrontation with experiment. If and when any agreement between superstrings and experiment is found, it will certainly justify an entirely new book on the subject.

I wish to thank Professor J. C. Pati for encouragement to reprint and expand "Dual Resonance Models." The Benjamin/Cummings Publishing Company generously assigned and transferred its 1974 copyright. I also thank Professor T. Kobayashi for the opportunity to give lectures on the superstrings Supplement at Tokyo Metropolitan University in April 1986. Finally, I thank Jody Gollan for typing the new camera-ready material.

Chapel Hill
May 1986

Paul H. Frampton

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ORIGINAL PREFACE*

Despite the fact that local field theory is successful in describing electromagnetic, and to a lesser extent, weak interactions, it seems to be plagued with difficulties when applied to strong interactions. Firstly, the available methods in field theory are largely tied to perturbation expansions in the coupling constant and the coupling constant for strong interactions is large; secondly, because of the proliferation of strongly-interacting particles it seems impracticable to associate a new field to each new particle.

Because of these problems, the S-matrix approach was developed which rejects the field as the important concept and attempts to study directly the transition matrix elements. This work is based on the fundamental postulates of (1) Poincaré invariance, (2) Cluster decomposition, (3) Analyticity, (4) Unitarity and (5) Crossing symmetry. The main difficulty here lies in disentangling the complicated non-linear relations implied by unitarity; in general, rather drastic simplifying assumptions must be made.

*To "Dual Resonance Models" (Benjamin, 1974).

During the last few years, however, some new light has been shed on the S-matrix approach through the introduction of the duality idea, and that is our present subject.

As is well known, the concept of duality in strong interactions was first arrived at in 1967 by Dolen, Horn and Schmid from the study of the constraints imposed by analyticity and crossing symmetry through the technique of finite-energy sum rules. It was found that the direct-channel resonances and the cross-channel Regge poles provided, in an average sense, equivalent descriptions of the same phenomena.

The notion of duality received its first precise formulation with the advent of dual resonance models, starting from Veneziano's proposal in 1968 of the Euler B function model for the four-point function. This model demonstrated how the direct-channel and cross-channel descriptions can be precisely equivalent for a sum over an infinite number of resonances. The presentation of this model clarified this question and precipitated a great deal of significant progress. First it was found that the model could be straightforwardly extended to a multiparticle amplitude embodying the same principles, and, more remarkably, that the resultant amplitude was completely factorisable on a finite degeneracy. Secondly, towards the end of 1969 Virasoro pointed out that for a particular intercept value there were sufficient gauge relations to allow the possibility of eliminating indefinite-metric ghosts, although the complete proof that this indeed happens was not arrived at until 1972.

The model thus exhibits enormous mathematical consistency: of course this simplest model is far from describing Nature—for example, the mass spectrum is quite unrealistic and there are no fermions.

There followed a search for more complicated and improved models. In 1971, Ramond, Neveu, and Schwarz developed a dual theory with several advantages over the earlier one. It added additional

degrees of freedom, and enlarged the gauge algebra, in such a way that ghosts were still absent, and fermions could be included in a consistent way. Subsequently, a variety of methods have been used to look for an even better model but although proposals exist no one has yet demonstrated that his particular model satisfies all the required postulates.

Despite the lack of realism, the construction of these models represents a significant advance in the S-matrix approach to strong interactions. It teaches us that we may try to satisfy the basic postulates in a resonance approximation, with the advantage that the implications of unitarity are greatly simplified for resonance exchange.

What follows has been developed out of lectures given at the Nordic School in Spøtind, Norway (January 1972), at Bielefeld University, West Germany (Autumn 1972), at Syracuse University, New York (Spring 1973) and at the Ettore Majorana School in Erice, Sicily (July 1973). The material has been up-dated, approximately to April 1974.

In Part I we introduce the phenomenological concept of duality after giving some elementary discussion of Regge poles and resonances. This explains the motivation for constructing the dual resonance models. Part II deals with the Veneziano function, its multiparticle generalisation and derives the exponential degeneracy of states. Here the very important projective group $O(2,1)$ is first introduced. In Part III the operator formulation of the model is analysed, making extensive use of the projective group. The no-ghost theorem is proved here.

The treatment of internal symmetry, particularly isospin, is made in Part IV. The difficulty of introducing broken symmetries (such as SU_3) is pointed out, and then the rubber string derivation of the Veneziano model is given. The main subject of Part V is the

introduction of fermions, and the principal properties of the Neveu-Schwarz-Ramond theory are worked through in some detail. In Part VI the symmetric group approach is used to classify the earlier models, and to lead the way towards improved ones. To correct, at least partially, for our theoretical bias we outline in Part VII some of the phenomenological applications of the generalised Euler B function formula. Finally, in an Appendix, we show how, in the limit of small Regge slope, dual resonance models reduce to lagrangian field theories.

Throughout, we give fairly complete derivations for all the algebraic and group theoretic results and only in a few less important cases are results cited without proof.

Over the last several years I have benefited in my knowledge of dual resonance models from interactions with many other theorists. A partial list includes: D. Amati, L. Brink, R. C. Brower, P. G. O. Freund, S. Fubini, M. Gell-Mann, P. Goddard, M. Jacob, Z. Koba (deceased), C. Lovelace, S. Mandelstam, Y. Nambu, A. Neveu, H. B. Nielsen, D. I. Olive, P. Ramond, R. J. Rivers, J. Scherk, C. Schmid, J. H. Schwarz, G. Veneziano and M. A. Virasoro. I am grateful to these, and others, for enlightenment.

Finally it is a pleasure to thank Mrs. Joyce McManus, Mrs. Betty Osborne, Frau Irmela Schmidts and Mrs. Marjorie Warner for typing the manuscript.

April 1974

P. H. Frampton

TABLE OF CONTENTS

Preface to Reprinted and Expanded Edition	v
Original Preface	ix
Part One: DUALITY	
1.1 Introduction	1
1.2 Definitions and Kinematics	2
1.3 Single Variable Dispersion Relations	10
1.4 Resonances and Regge Poles	13
1.5 Superconvergence and Finite Energy Sum Rules	22
1.6 FESR Duality; Schmid Loops	26
1.7 Harari-Freund Ansatz	33
1.8 Exchange Degeneracy	34
1.9 Duality Diagrams	37
1.10 The Situation of Mid-1968	41
1.11 Multiparticle Production	45
1.12 Summary	50
References	51
Part Two: MULTIPARTICLE DUAL MODEL	
2.1 Introduction	55
2.2 Veneziano's Beta Function and Its Properties	56
2.3 Five-Point Function	67
2.4 N-Point Function	71

2.5	Koba-Nielsen Form and Projective Invariance	77
2.6	Operator Factorisation and Level Density	83
2.7	Satellite Terms	90
2.8	Amplitude for Pion-Pion Scattering	95
2.9	Shapiro-Virasoro Model	99
2.10	Summary	104
	References	106
Part Three: OPERATOR FORMALISM		
3.1	Introduction	109
3.2	Projective Group	110
3.3	Gauge Invariance	122
3.4	Operatorial Duality	129
3.5	Unit Intercept	136
3.6	Null States	142
3.7	Critical Dimension	148
3.8	Physical State Construction	157
3.9	Twisting Operator	165
3.10	Multireggeon Vertex	171
3.11	Summary	179
	References	181
Part Four: INTERNAL SYMMETRY		
4.1	Introduction	184
4.2	Multiplicative Internal Symmetry Factor	185
4.3	Factorisation of Unequal Intercepts	190
4.4	The Rubber String Model	194
4.5	Baryons and Exotics	207
4.6	More on the Rubber String	219
4.7	Summary	234
	References	236
Part Five: SPIN		
5.1	Introduction	238

5.2	Multiplicative Spin Factor	239
5.3	Free Fermions (Ramond)	247
5.4	Dual Pion Model (Neveu and Schwarz)	257
5.5	Spectrum	266
5.6	Boson-Fermion Couplings	275
5.7	Generalised Projective Invariance	284
5.8	Non-Planar Extension	291
5.9	Summary	293
	References	295
Part Six: SYMMETRIC GROUP		
6.1	Introduction	298
6.2	Methods of Attacking the Intercept Problem	299
6.3	Four-Meson Amplitude; Symmetric Group	301
6.4	Regge Behaviour and Analytic Properties	306
6.5	Explicit Construction	309
6.6	Four-Pion Amplitude	315
6.7	Possible Connection to Three-Quark Baryons	322
6.8	Multiparticle Extension	325
6.9	Classification of Dual Resonance Models	329
6.10	Multipion Amplitude	334
6.11	Spin-Lowering Symmetry	339
6.12	Factorisation	342
6.13	Summary	356
	References	358
Part Seven: PHENOMENOLOGICAL APPLICATIONS		
7.1	Introduction	362
7.2	Baryon-Antibaryon Annihilation	364
7.3	Meson-Nucleon Scattering	368
7.4	B_5 Phenomenology	375
7.5	Single-Particle Inclusive Spectra	383
7.6	Many-Particle Inclusive Spectra	391

7.7	Summary	392
	References	394
Appendix: ZERO-SLOPE LIMIT		
A.1	The $\lambda\phi^3$ Limit	398
A.2	Yang-Mills Field Theory	401
A.3	Regge Slope Expansion	410
	References	414
Supplement: SUPERSTRINGS		
S.1	Introduction	415
S.2	Gravitation	417
S.3	Ten-Dimensional Supersymmetry	424
S.4	Non-String Kaluza-Klein Theory	427
S.5	Anomaly Cancellation	440
S.6	One-Loop Finiteness; Modular Invariance for Closed Strings	446
S.7	Heterotic string	475
S.8	Superstring Phenomenology	486
S.9	Summary	499
	References	500
Reprints:		
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	Index	525