Chapter 7
Theoretical Exaptation in String Theory

> *[W]e must have both felt that it must be good for something, since it was just such a beautiful, tight structure.*
>
> John Schwarz

In a reprint volume on *Dual Theory*, published in 1974[1], David Olive had this to say about the status of the dual theory and its newly discovered potential for describing more than just hadrons[2]:

> The whole motivation of the dual resonance theory was in connection with strong interaction physics. Now we have seen the remarkable fact that in the (we hope) unlikely event of this being wrong, the theories of the other interactions, weak, electromagnetic, gravitational, appear as different special cases of the same dual theory. The most optimistic point of view is that we are on the way to a unified theory of all the interactions, but if not, we still have the most general and powerful theory yet found in the sense of generalizing all previously known theories of interest [28, p. 150].

One might have thought that this clear statement of the potential unifying power of the dual models might have led to much frenzied work in unpacking the details. Olive himself thought of the new point of view as a “conceptual revolution” [29, p. 35]. However, his efforts to motivate the unified dual models fell largely on deaf ears, with the majority of physicists finding it too risky a project.

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[1] Note that this was the first volume of the *Physics Reports Reprint Series*, aimed at providing overviews of rapidly changing fields, in their early stages. This first volume spans exactly the transitionary period, charting the development of dual models from a pure hadron theory, potentially to a unified theory, and from a dual theory without a really clear physical grounding, to a theory of relativistic quantum strings. It also leads up to the cusp of string theory’s existence as a description of strongly interacting systems—though as the quotation from Olive (written in 1974) below shows, it wasn’t completely clear cut that the string models would *not* provide a good model of hadrons.

[2] Olive was referring to the then new results of Yoneya and Scherk and Schwarz, as well as earlier related results on the content of the zero-slope limits of dual models. We will discuss these below. What Olive didn’t refer to in his account was the rescaling that was also required to obtain a theory able to reproduce the predictions of general relativity at observed energies, rather than some theory whose fundamental excitations lived at the hadronic scale.

D. Rickles, *A Brief History of String Theory*, The Frontiers Collection,
DOI: 10.1007/978-3-642-45128-7_7,

Nevertheless, the most curious feature in the history of string theory has to be this transition that occurs in its function, from a description of the forces binding protons and neutrons to a description of gravitational and other interactions. This is perhaps the most extraordinary case of 'theoretical exaptation' in the history of physics.[3] One can see from Olive's remarks that the seed of grand unification had already been planted by 1974. In a similar vein, Scherk and Schwarz write of the still relatively new results on zero-slope limits:

> [A] scheme of this sort might provide a unified theory of weak, electromagnetic, and gravitational interactions. The gauge bosons and leptons would be identified with open strings and the graviton with the closed string [30, p. 347].

This, in essence, corresponds to the barest modern understanding of string theory, though later work would show that the links between open and closed string descriptions (and therefore between gauge and gravity) were far more complicated.[4]

There are, in fact, similarities between this shift within string theory and the way in which gauge theory developed and transformed in its early days, including the belief that the theory was too beautiful not to be useful for something. Recall that gauge theory was devised by Hermann Weyl in 1918 (in the context of classical field theory) as a way of unifying gravitation and electromagnetism, with his principle of *eichinvarianz* connecting the electromagnetic potentials ψ_i and g_{ik}. The theory involved the idea that parallel transported vectors experience a path-dependent change of length of: $\exp(\gamma \int_C A \cdot dx)$. It turned out to be dysfunctional in this environment for solid experimental reasons, as had been pointed out by Einstein. But it was later revived in the new 'quantum environment', involving not the non-integrability of length measurements, but of *phase*. Just as Vladimir Fock and Fritz London simply changed real into complex numbers—so that electromagnetic potentials were reinterpreted as linked with the components of the quantum wave-function Ψ—so string theory just had to adjust the value of the string constant to get a theory of quantum gravity. Of course, this simple modification has dramatic consequences with respect to the physical interpretation of the theory. Various elements of theoretical structure are impacted on; not least the critical spacetime dimension of the theory, which can be viewed through the lens of the dynamical nature of geometry of general relativity. This itself then suggests an entirely new range of tools, concepts, and techniques that can be employed in the further development of the theory.

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[3] "Exaptation" is, of course, a term from evolutionary biology introduced by Steven Jay Gould and Elizabeth Vrba [20], referring to the shift in function of some trait or aspect of physiology over time, so that it is 'co-opted' for another use. To the best of my knowledge, it has not previously been employed for use in the context of historical studies of scientific theories, but I think it entirely appropriate here.

[4] Recall that given the restrictions on the intercept $\alpha(0)$, to either 1 or 2, then we will get a pair of Regge trajectories, each with infinitely many particles lying on it, but the former trajectory will contain a massless spin-1 (vector) particle while the latter will contain a massless spin-2 particle (identified as a pomeron in the earliest phases).

This chapter will explore this transitionary phase of string theory's history[5], taking the story up to the early 1980s, at which point the notion that string theory might offer a mathematically consistent 'unified quantum theory' was fully known, if still not yet fully understood or commonly pursued. The next leap forward (the subject of the first chapter in Part III) was the isolation of a phenomenologically suitable model.

7.1 The Role of the Scherk Limit

A vital piece of structural knowledge that was required by the idea that the function of string theory could be shifted was the notion that the dual models reduced to field theories in specific limits, namely those for which $\alpha' \rightarrow 0$ (the zero-slope or 'Scherk' limit.[6] The method of transformation involved the Mandelstam-Regge trajectory slope, modifying it from approximately $1/GeV^2$ to $10^{-38}/GeV^2$.[7] In terms of length, the shift is one of 20 orders of magnitude, from $l_s \sim 10^{-13}$ cm (the scale of hadrons) to $l_s \sim 10^{-33}$ cm (the Planck length, at which quantum gravitational effects become non-negligible). In terms of string tension, given that it goes as $1/l_s^2$, we find a shift of 40 orders of magnitude. As the slope is reduced, the masses of any initially massive particles increases, going to infinity in the zero slope limit. Only the massless states survive this limit and these correspond to the known classical field theories. As we have already seen, Jöel Scherk was responsible for figuring this out. The initial suggestion for thinking about what happens when the slope goes to zero seems to have come from Roland Omnès, during Scherk's Doctorat d'Etat lecture.[8]

Scherk's final papers were on supergravity, and in particular on dimensional reduction and spontaneous compactification, and the idea of using the compact dimensions as physical resources. Indeed, following the discovery that dual models reduce to Einstein gravity, Scherk appears to have increasingly diverted his attention to gravity.[9] Schwarz had been visiting the Ecole Normale Supérieure in Paris one year before Scherk died. During that year they worked on their paper entitled "How to Get Masses from Extra Dimensions" (see [34] for the published version).

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[5] What Yuri Manin has called a "romantic leap" [26, p. 60]. Gomez and Ruiz-Altaba call it "a healthy extrapolation" [19, p. 5].

[6] As we saw earlier, Scherk had initially derived a ϕ^3 quantum field theory, but later work with Neveu showed that a Yang-Mills theory resulted.

[7] In this Scherk (small-string) limit (where zero slope $\equiv$ infinite tension) the spin-2 massless mode (the graviton) persists and couples in a generally covariant manner, as in Einstein's theory of general relativity cf. [13, p. 373].

[8] As Omnès points out, this was a kind of examination, for which he was one of the jury members (private communication). Gervais recalls Omnès' remark occurring over lunch in the cafeteria of Orsay [15, p. 410].

[9] However, it seems Scherk was not completely comfortable with supergravity. As David Olive recalls, "I remember Joël Scherk complaining later that he felt obliged to work on supergravity whereas his real conviction lay with string theory" [29, p. 355]. We can guess that these were career-based obligations and peer-pressure.

The zero slope limit was the central device that enabled the dual string model to morph into the superstring theory we know today, with the problematic massless particles given a realistic interpretation. The compactification techniques he devised (which we return to later), to reduce critical to observed dimensions, are central to the generation of phenomenologically acceptable physics from superstrings. As Schwarz wrote at the Second Aspen Winter Conference on Physics, in 1987, "two of the most troubling features of string theory for application to hadronic physics could be turned into virtues if the goal was changed" [33, p. 269]—the zero slope technique and compactification models were central to this new-found virtuous status.

One might also mention that the softness of the scattering amplitudes, that had posed empirical problems with the hard-scattering experiments on hadrons, would also serve as a further virtue in this case since it tames the otherwise fatal ultraviolet divergences of gravitational interactions. However, the relationship between the divergences and non-locality of strings took longer to fully understand.

7.2 Dual Models of Everything

By 1975, Tamiaki Yoneya was able to write:

> By its string formulation, the dual-resonance theory has been acquiring a unified and clear physical picture. In particular, we are now able to treat interacting reggeons and pomerons, from the outset, by considering the interaction among open and closed strings [41, p. 440].

As we have discussed already, one of the (initially) embarrassing features of the dual model was that in, what was interpreted as the closed string sector of the general framework there was a spin-2 particle which was forced, by the gauge invariance required by the absence of ghosts, to be massless. It became clear to at least a handful of people that this particle had the properties required by the graviton (the carrier of gravitational force), and that given this it would be forced to behave in a generally covariant fashion. David Olive recalls that the idea that the dual models might therefore provide a unified framework for gauge and gravitational interactions was discussed as far back as 1971:[10]

> The price that the Dual Resonance Model has to pay for consistency with fundamental principles is that it looks increasingly less like a theory of strong interactions and more like a unified theory. Not only does it possess massless gauge particles but also massless gravitons.

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[10] In fact, Keiji Kikkawa (just as he was preparing to leave for his new position at CUNY) and Hikaru Sato considered the compatibility of gauge boson interactions with the dual resonance model in 1970 [24], though not using the varying slope method, which had yet to be introduced. They were concerned with the incorporation of the electromagnetic and the weak interactions in the dual resonance scheme (there is no mention of gravitation). Bars, Halpern, and Yoshimura [3] also considered a unified theory of all non-gravitational interactions in a way that was, as they acknowledge, heavily influenced by Neveu and Scherk's earlier work on the connection between dual models and Yang-Mills fields—see also [2] in which Bardakçi and Halpern consider what they call "M-models" (essentially an early gauge theory of hadrons) that are also tightly bound to Neveu and Scherk's work.

> Of course the same was true of the dual fermion theory (if indeed it does really exist) and it had the innate advantage of possessing fermions. As I remember, this idea of unification of gauge and gravitational interactions was much discussed by the community in CERN Theory Division in the year 1971–1972 even though this was before the discovery of asymptotic freedom and the formulation of the Standard Model [29, p. 352].

There were several independent generalisations of the dual models to gravity and other non-hadronic interactions—note that the title of this subsection, "Dual Models of Everything," is borrowed from Green, Schwarz, and Witten's textbook [22, §1.2]. The root of these alternative applications of dual models was, later on, the troublesome spectrum of massless particles, including massless spin-1 and spin-2 particles. The massless spin-2 case is especially interesting since, as has been known since the late 1930s (thanks to Wolfgang Pauli and Markus Fierz[11]), it corresponds to the expected features of a gravitational force carrying particle. However, initially the particle was not treated as having anything to do with gravity, and so was named the 'pomeron' instead.[12]

Schwarz and Scherk are usually credited with instigating the gravitational application of dual models. Yet, as Schwarz points, gravity was at that stage simply not in the toolkit of most particle physicists. Schwarz (and, one can guess, Scherk) learned general relativity later, as a result of the potential application of dual models to gravity:

> We knew that that was an issue, but it wasn't our problem; we were trying to understand the strong interactions. And in those days physics was much more compartmentalized than it is now. The first thing that people who were brought up in particle physics were taught was that you can forget about gravity, because if you just look at the force between two protons, or even between an electron and a proton, the gravitational force compared to, say, the electric force, is smaller by ten followed by 38 zeros or something. It was just fantastically negligible. So we were taught to forget about gravity. It had nothing to do with our problem. Particle physicists wouldn't talk about gravity. I mean, if anyone tried to, they'd be viewed as a crackpot. It wasn't part of the problem (http://resolver.caltech.edu/CaltechOH:OH_Schwarz_J, p. 27).

Hence, though we now think of the 'killer app' of string theory as its consistent implementation of quantum gravity, no one in the dual model community was concerned with that problem at the time: certainly not the particle physicists, who would have been the natural audience, given the concepts and methods employed. The killer app simply didn't take at its inception and it is important to reiterate that this was *not*

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[11] It is interesting to note that Alton Coulter brought out a paper [7] explaining the relationship between massless spin-2 fields and gravitational theory the same year as Scherk's first paper on the zero slope limit, 1971. Coulter mentions the Fierz and Pauli result, though he proposes a modified version of the theory based on the physical components of the spin-2 field, rather than potentials.

[12] There was something of a battle of names over this Regge intercept second hadron: Mandelstam, Chew, and other central figures can be found calling the particle the 'Pomeranchon'. One can find also a more extended version, 'Pomeranchukon,' to fit more of Pomeranchuk's name in! Throughout the late sixties and early seventies all of these names were utilised. Later 'Pomeron' became the accepted term—Gribov introduced the Pomeron concept, though credit is usually given to Gell-Mann (via Geoff Chew) with coining the term 'Pomeron' to refer to the vacuum pole (i.e. a pole with vacuum quantum numbers).

the result of QCD being the stronger theory.[13] To compare Scherk and Schwarz's modified dual string model with QCD is to compare apples and oranges: very different fruit. To 'sell' strings, they needed the research landscape to alter in such a way that string gravity was well adapted to it. John Schwarz is quite rightly credited as being one of the main researchers keeping string-gravity alive while this change happened—though, Schwarz was also part of the 'refashioning' of the wider research landscape too, as I shall explain in the next chapter.

Hence, at the time of their initial attempt to forge a new path for the dual models, they were not especially interested in the conflict between quantum theory and general relativity:

> [I]t wasn't a problem that we were particularly concerned about. However, when Scherk was here in '74, at some point in our deliberations we said, "Just for the fun of it, let's see whether this massless spin-2 particle behaves in the right way to give the standard gravitational force of the Einstein theory of general relativity." And having posed the question, it wasn't actually very hard to answer by invoking some appropriate theorems and making the case that indeed that was right. [.] And the reason we found this exciting was that we knew that string theory was going to give a consistent quantum theory. [.] And it became clear to both of us, immediately, that this was the way to make a consistent quantum theory for gravity. So we figured that we'd just tell the world and they'd all get excited and start working on it (http://resolver.caltech.edu/CaltechOH:OH_Schwarz_J, p. 28).

Given that the framework promised a consistent framework for quantum gravity one might have expected the quantum gravity community to jump on it. But, as Schwarz goes on to note, "Nobody took it seriously—not even the relativists or the people who had been working on string theory before. Nobody!" (ibid., p. 29).[14] To reiterate, the string theory of gravity and non-hadrons, was a new theory that started more or less in 1973/4. Like most new theories, it takes time to generate interest. One can look to other quantum gravity proposals (Roger Penrose's twistor framework, for

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[13] For this reason, I think Schwarz is mistaken in assigning the 'blame' over the delayed uptake of string theory as a fundamental theory of all interactions to "the stigma associated with its origins [in S-matrix theory]" [32, p. 5]. The theory was, at the time, still plagued by a tachyon, and still had the curiosity of the additional spacetime dimensions (despite the potential dynamical explanation in a gravitational context). On the latter, in 1974, Fubini associated the varying of the number of spacetime dimensions with "science fiction" [14, p. 5], —though he did not dismiss the approach; but rather thought that the $d = 26$ and $d = 10$ results "should suggest further study on the rôle of dimensionality in the general structure of physical theories" (ibid.). One might add to this that gravitational physics (*prima facie* a natural habitat for the newly transformed string theory) was still not long out of a transformation of its own, from a field that had become synonymous with 'crackpot science' to one based on solid experimental and observation evidence. At this stage of its development, string theory might well have looked like just another unified field theory, which is precisely what the relativity community was keen to avoid.

[14] This is a slight exaggeration. I suspect that had they pitched string theory more along the lines of what the general relativity and quantum gravity community were used to, engaging with their concerns, they might have fared better. I might add that Schwarz and Scherk did receive an 'honourable mention' (though along with 29 others!) in the 1975 Gravity Research Foundation essay competition for their paper "Dual Model Approach to a Renormalizable Theory of Gravitation" (a strong year, in which Roger Penrose took first prize and Julian Schwinger second).

example) to see a similar phenomenon.[15] What is curious about the dual models of non-hadrons, of course, is that they were discovered via dual models of hadrons, and probably would not have been otherwise—here perhaps is a difference from the case of Weyl's gauge theory: there was an *immediate need* (rather than basic survival) driving that case of exaptation.

The introduction of gravity suggested to Scherk and Schwarz that the problem of the mismatching dimensions might be given a dynamical explanation: general relativity allows for features of space–time to be determined by equations of motion, so perhaps the determination of the space–time dimension is not so bad after all!

> You see, before it had been a problem. When we were just doing strong interactions, it didn't make sense. But in gravity, the geometry of space and time is determined by the equations of the theory. So it became a possibility that the equations of the theory would require that six of the dimensions, for some reason, would curl up into some invisible little ball or something, and then it could be perfectly consistent with observation. It wouldn't make sense to give that kind of a story if you were just doing strong interactions, but in a theory of gravity, that kind of story made sense. We certainly understood that (ibid., p. 30).

This dynamical feature of space–time geometry became known as "spontaneous compactification", and can be found in Scherk's work with Cremmer, from 1976 [8, 9]. However, this is related to 'dimensional reduction' which goes back farther.

Directly influenced by Neveu and Scherk's earlier work [27][16] showing that Yang-Mills field theories can be given a tree approximation using the zero slope technique, Tamiaki Yoneya had independently realised that the low-energy behaviour of dual models was equivalent to Einstein gravity too, from the scalar amplitudes of the Virasoro-Shapiro model (again, with $\alpha' \to 0$ and fixed $g\sqrt{\alpha'}$). Since he explicitly refers to quantum gravity along the lines of the "Gupta-Feynman" [38, p. 951], perturbative approach[17], we can infer that the links Feynman and others had drawn between Yang-Mills theories and general relativity were behind the extension to gravitation in this case. Yoneya explicitly interprets the massless spin-1 and spin-2 states, required by the no-ghost condition, as a photon and a graviton [39, p. 1907].[18]

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[15] Rather interestingly, Chang and Mansouri mention in 1971: [4, p. 2541], some potential overlap between Penrose's twistors and dual string models of hadrons, in their discussion of the introduction of spin degrees of freedom onto the time-evolved string's two-dimensional surface (they didn't use the worldsheet terminology).

[16] In his reminiscences, Yoneya recalls that he received a preprint of the Neveu-Scherk paper in 1972, from M. Minami (a fellow dual theorist from the Research Institute of Mathematical Sciences in Kyoto)—Minami was offering comments on an earlier preprint of Yoneya's (on the nature of the gauge principle in open string models) that had in fact been rejected. Yoneya switched to the closed strings of the Virasoro-Shapiro model, finding gravity. However, he claims to have been "prejudiced against general relativity" on account of the dominance of the S-matrix programme, so his idea languished. It was the resurgence of interest in gauge theories that spurred him on into revisiting his idea.

[17] That is, the approach in which the metric tensor is split into two parts, $g_{\mu\nu} = \delta_{\mu\nu} + \kappa h_{\mu\nu}$ (where $\kappa^2 = 16\pi G_{Newton}$), with the Lagrangian then expanded in powers of κ.

[18] Of course, we now associate these with open and closed string descriptions respectively, but Yoneya only mentions strings in a brief appendix of his paper. This highlights the fact that even into the mid-1970s there was a parallel operator algebraic approach that was capable of discovering

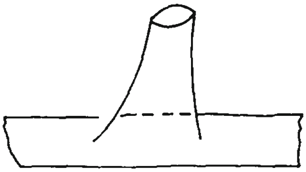

Fig. 7.1 Emission of a *closed* from an *open* string according to Ademollo et al. *Image source* [1, p. 193]

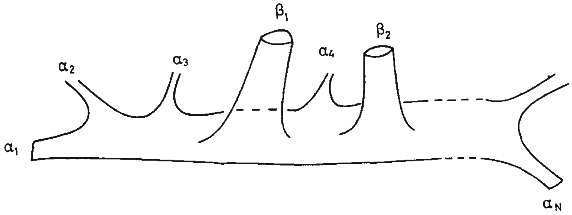

Fig. 7.2 A combination of ‘*open* → *open*’ transitions (described by the vertex $V_\alpha(z, k)$) and ‘*open* → *closed*’ transitions (described by the *vertex* $\omega_\beta(z, \bar{z}, k)$). *Image source* [1, p. 196]

One can also find a clear statement of the existence of a graviton “coupling universally with the energy momentum tensor of the string” in a 1974 paper of the Ademollo et al. collaboration [1, p. 191],—that is to say, the ‘strong graviton’ just *is* a graviton. They use this universality property to develop a scheme for coupling open and closed strings. However, they make no attempt to rescale the physics to describe a gravitational physics coupling according to Newton’s constant, and are primarily concerned with constructing a *unified* model capable of incorporating both open and closed strings, in interaction, thus bringing together the generalised Veneziano model and the Shapiro-Virasoro models. The basic vertex, $\omega_\beta(z, \bar{z}, k)$, for the emission of a closed from an open string is achieved by treating the closed string interaction as an external field (see Fig. 7.1).

This vertex can be combined with the vertex, $V_\alpha(z, k)$, of the original Veneziano theory (for open → open transitions) to write down complex amplitudes, such as that depicted in Fig. 7.2.

Before leaving this topic, mention should be made of a further, quite distinct, attempt to forge a connection between dual string theory and general relativity, by Takabayasi [36], this time based on an analysis of general covariance in string theory and a formal analogy between this and general relativity. Takabayasi bases his approach on the geometric string model of Nambu-Gotō that he had played a role in. However, the connection in this case is a purely formal one, involving an overlap of mathematical formalism, and there is no suggestion that gravitation is involved in, what for Takabayasi are still hadronic strings.

(Footnote 18 continued)
many of the features that we often associate with the more geometrical, string picture. He made the connection to closed strings explicit in his 1975 paper on dual string models and quantum gravity [41].

7.3 The GSO Projection and ‘Real’ Superstrings

One of the most serious flaws with the dual string models had been the persistent presence of a tachyon located at the lowest mass state. For example, in the 26 dimensional Veneziano model, we find the following spectrum containing $M^2 = -1$:

Mass^2	J (spin)
-1	0
0	2 (also: spinless dilaton and 2-form)
1	≤ 4
2	≤ 6
$\vdots$	$\vdots$

This was finally and fully resolved in 1976, within the supersymmetric model of Gliozzi, Scherk, and Olive, in their paper “Supersymmetry, Supergravity Theories and the Dual Spinor Model” [17]. The method involved the imposition of a certain chiral projection that suppressed (‘truncated’) a large sector of the states, including that containing the tachyon, so that the ground state (for the bosonic sector: NS) instead comprises a massless graviton, a massless scalar, and a massless antisymmetric tensor. The NSR sector (also containing left-handed Majorana fermions), is also tachyon-free and has a massless spin $3/2$ state (then called a “hemitrion” rather than a gravitino[19]) and a massless scalar (see Fig. 7.3).[20]

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[19] As is so often the case, Murray Gell-Mann was behind this earlier naming scheme. Peter van Nieuwenhuizen describes, in his Dirac lecture from 1994, how he and Gell-Mann browsed through dictionaries searching for a “venerable name” for the massless spin 3/2 particles. They settled on ‘hemitrion’ since it means ‘half-3’. Alas, as is also so often the case, the editors of *Physical Review* were not keen on the name, and suggested their own: “massless Rarita-Schwinger particle”. He notes that Sidney Coleman and Heinz Pagels coined the current name of ‘gravitino’ [37, pp. 14–15].

[20] There were some relevant earlier steps along the way to this result. For example, Clavelli and Shapiro [5] made a detailed study of G-parity states in the NS-model, in their paper on Pomeron factorization, showing that both odd and even G-parity states contribute. They also consider projection operators onto the G-parity states and the possible “cancellation of the tachyon pole” (noting that there is no such possibility from the positive-G-parity part: p. 505). Fairlie and Martin performed a “systematic replacement of the factors in the one-loop integrals for the original model by factors incorporating the anticommuting elements ψ_i” (where $i = 1, ..., N$ are linked to the N Koba-Nielsen variables and form an anticommuting Grassmann algebra, $\psi_i \psi_j + \psi_j \psi_i = 0$: [10, p. 375]; see also [11]). They were able to show that odd G-parity Pomerons disappeared (cf. Mandelstam’s review of dual-resonance models, in which he also explicitly notes how one could use this approach to “exclude off g-parity particles from the Pomeron sector of the N.S.R. model” [25, p. 348]. Note that these issues were dealt with at length in David Martin’s PhD *Investigations into Dual Resonance Models*, completed under Fairlie at Durham between 1971–1974: http://etheses.dur.ac.uk/8277/1/8277_5278.PDF. Michael Green [21] also made inroads on similar problems in 1973. In 1978, in an interesting review of the ‘spinning string theory from a modern perspective,’ John Schwarz writes that “[i]t was clear from the beginning that one could restrict the [NSR] model

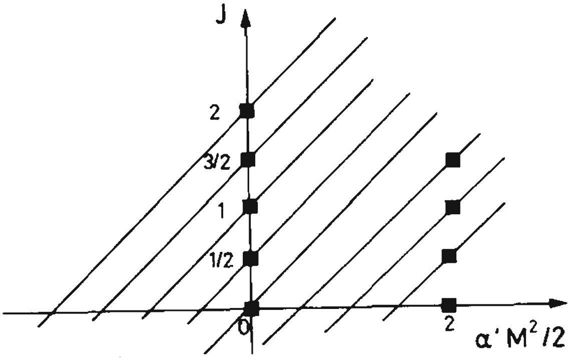

Fig. 7.3 A Chew-Fraustchi plot of the spectrum of states of the supersymmetric NSR model (for *closed strings*) showing the elimination of the $M^2 = -1$ (tachyonic) state and suggesting supersymmetry between the bosons and fermions (i.e. an equal number of bosons and fermions located at each mass level) [17, p. 281]

The truncation also generates a spacetime supersymmetric spectrum of states, associating one-to-one at each mass level, bosons and fermions in ten dimensions[21], so that (in the NSR theory) there is at each mass-level an equivalence between the number of physical states in the bosonic and fermionic sectors (which points to the existence of supersymmetry in the full 10-dimensional theory).[22] This work produced what would later be called 'Type I' superstrings (where the 'I' refers to the number

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to the subspace of even "G parity" particles, which is free from tachyons ... [but] this restriction was not advocated partly because of our commitment to hadronic interpretation, partly because of other hopes for eliminating the tachyon, and partly because of the concern that fermionic coupling would restore the odd-G states through duality" [31, pp. 433–434].

[21] Of course, as we saw earlier, it was already known that there existed a two-dimensional worldsheet supersymmetry (as they mention in their paper), but not yet a spacetime (or 'target space') supersymmetry. An earlier version of the paper submitted to *Physics Letters B* contains the abstract: "We find that the spinor dual model is locally supersymmetric not only in the two-dimensional surface spanned by the string, but also with respect to the embedding space–time" [16, p. 282].

[22] In fact, they hedge somewhat by writing that "this model has a good chance of being supersymmetric" [16, p. 266], noting later that a full proof would demand a definition of the supersymmetric transformations that exchange the NS (bosonic) and R (fermionic) states (ibid., pp. 267–268). Their own proof involved an identity that had already been proven by Carl Jacobi in 1829 (his *Aequatio identica satis abstrusa*)—yet more evidence for Fairlie's remark that "String theory is more like something dragged out of the nineteenth [century]!". This involves another instance of the serendipity resulting from 'turning to the maths books' for an expected answer. Gliozzi writes: "I knew I had to look for some identity involving Jacobi theta functions. I took from the shelf of mathematical book ... a copy of Whittaker and Watson ... [and] it magically opened on page 470, where the following exercise is proposed:

$$\text{`Shew that : } \frac{1}{2}\left[\prod_{n=1}^{\infty}(1+q^{2n-1})^8 - \prod_{n=1}^{\infty}(1-q^{2n-1})^8\right] = 8q\prod_{n=1}^{\infty}(1+q^{2n})^8.\text{'} \qquad (7.1)$$

It was exactly the sought after formula!' [18, p. 455]. That is, the formula describes (with its signs capable of describing bosons [NS] and fermions [R]) their level-by-level equality. As Gliozzi puts it: "[t]he left-hand side is the relevant part of the generating function of the NS physical states after removing the odd G-parity sector, while the right-hand side is the analogous function for the Ramond states, after projection on the Majorana-Weyl spinors; the factor 8 comes from the degeneracy of the ground state fermion" (ibid.).

of supersymmetries) and marks the birth of the modern understanding of (consistent) superstrings *qua* supersymmetric strings. Of course, the 'dual spinor model' in this paper simply refers to an embryonic version of superstrings and highlights the fact that string theory (even in its exapted form) was still connected by an umbilical cord to the old dual resonance models.

As Gliozzi remembers it, he began discussing these ideas (initially with Scherk) leading to the GSO result while "under the influence" of the recent work on supergravity, that was taking place in the offices next door to his [18, p. 545].[23] His idea was to extend this work to RNS [Ramond-Neveu-Schwarz] strings. Using the Scherk limit they found that the RNS theory defined a $d = 10$ supergravity theory. Applying the kinds of compactification techniques Scherk had developed with Cremmer, they were able to show that pure supergravity in $d = 10$ generates supergravity coupled to matter in four $d = 4$. The massless spin 3/2 particle mentioned above was the signal that supersymmetry was involved (since such a particle only consistently couples to supersymmetric matter), so that each physical state in the NS-sector should be partnered with a physical state in the R-sector.[24]. It was then the fact that such a partnership breaks down for both the tachyon[25] and the NS-subsector satisfying $\alpha' M^2 = n - 1/2$ (the odd-G-parity sector, where the G-parity operator combines charge conjugation and a 180° rotation about the second axis of isospin space), that formed the basis for the projecting out of such sectors:

> we [Gliozzi and Scherk] discovered that this sector transformed a right-handed fermion into a left-handed fermion, therefore it decoupled altogether if the right-handed fermions were projected out using Weyl spinors. Moreover the fermion-fermion and the fermion-antifermion states had the same spectra as bosonic bound states. In order to avoid infinite degeneracy of the bosonic spectrum we were led to require that the fermions satisfy also the Majorana condition. The resulting projected model, as tachyons had been removed, was the first example of a totally consistent string theory. Only later, thanks to the contribution of David Olive, we realized that the requirement of the Majorana-Weyl condition is very constraining and is possible only if d is 2 modulo 8 [18, pp. 454–455].

In sum: half of the fermion states and the odd G-parity (boson) states are removed, leaving the bosonic and fermionic spectra evenly-balanced (and recovering, in a natural way, $d = 10$ for the RNS model, as a result of the joint imposition of Majorana and Weyl restrictions on the Dirac spinors).

This work heralded (though after a brief 'intermission') the beginning of a new wave of dimensional reduction in string theories. In this case it included a link between the compact manifold and the low energy (four dimensional) properties that

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[23] Indeed, in [17] the work explicitly aims to tie dual model research to that taking place in supergravity theories (see p. 254).

[24] One finds that the transverse (physical) Fock spaces associated with the Neveu-Schwarz and Ramond theories both decompose into a pair of invariant subspaces (chiral projections) under the transverse subgroup, $SO(8)$, of the Lorentz group in $d = 10$, $SO(9,1)$

[25] Initially the tachyon elimination was a major motivation, along with the derivation of supergravity, but later work on higher-loop (non-tree level) amplitudes, placed the GSO projection even more centrally in the superstring programme, revealing that the truncation it enforces is in fact required in order to preserve unitarity and modular invariance (see [35, p. 285], [23]).

remain after the compactification. In particular, the preservation of supersymmetry in higher dimensions depended on features of the manifold, with a torus leaving invariant *all* of the supersymmetry of the higher dimensional theory. However, it wasn't until Michael Green and John Schwarz's work on new superstring theories, from 1980 onwards, that a version of string theory with explicit spacetime supersymmetry was constructed.

7.4 Summary

We have seen how the Scherk limit, discovered during the heyday of dual models, was utilised as a tool for converting the function of dual models from strong interactions (with 'strong photons' and 'strong gravitons') to a theory of non-hadrons (electrodynamics, Yang-Mills theory, and gravitation). This shift in function led to new (positive) ways of viewing what were previously viewed as insurmountable problems: the presence of massless particles in the dual model spectra, and the requirement of 26 or 10 dimensions of spacetime, both demanded by consistency. The remaining problem of the tachyon was also finally ironed out by following connections with supergravity, with spacetime supersymmetry offering a mechanism for controlling the theory. The next chapter looks at the steady rise of string theory work in the early '80s, followed by the dramatic shift in factors triggered by Green and Schwarz's anomaly cancellation proofs.

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