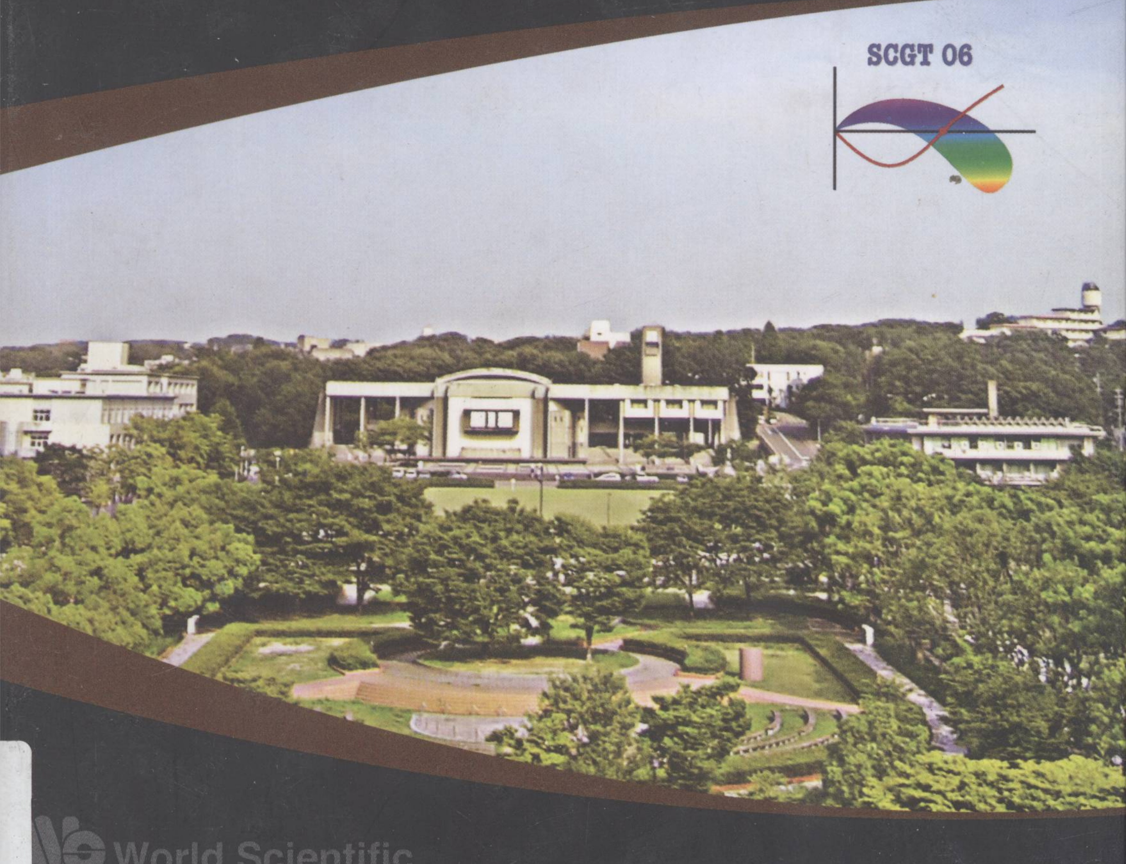
The Origin of Mass and Strong Coupling Gauge Theories

Proceedings of the 2006 International Workshop

M. Harada, M. Tanabashi & K. Yamawaki
Editors



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PREFACE

Origin of Mass is the most urgent problem to be solved in particle theory and is the main target of the upcoming LHC experiments. Also, detailed mechanism of the origin of mass of hadrons should be tested through chiral symmetry restoration and deconfinement in QCD by the ongoing RHIC and upcoming LHC heavy ion collisions.

Based on the strong coupling gauge theories (SCGT), many Composite Models such as the Walking Technicolor, Top Quark Condensate, Little Higgs, Higgsless model, etc. have been proposed over decades to explain the dynamical origin of the mass of elementary particles, and are ready to be tested in the LHC. Many mechanisms proposed for the chiral phase transition in QCD should also be tested in the RHIC/LHC experiments.

The main obstacle of the strong coupling theories like QCD is the difficulty at obtaining the nonperturbative solution and making a definite prediction to be precisely compared with the experiments. Apart from the first-principle method of the lattice gauge theories, several alternative methods have been investigated to draw some, though not completely quantitative, predictions: Effective field theories (Chiral Perturbation Theory) with/without Hidden Local Symmetry (Moose or deconstructed extra dimensions), large N expansion, ladder Schwinger-Dyson Equation (gap equation) & Bethe-Salpeter equation, etc. as well as hints from some exact nonperturbative results of SUSY gauge theories.

Since the first meeting of the Nagoya SCGT Workshop held in 1988 (SCGT 88), which was motivated by the Walking Technicolor and some composite ideas like Hidden Local Symmetry, we have organized four SCGT workshops in 1988, 1990, 1996 and 2002 for discussing various developments of SCGT and new ideas. Physicists including many leading physicists from all over the world came together for the Workshops and created a new phase at each meeting.

From November 21-24, 2006, facing the start of the LHC experiment, we organized the fifth Nagoya SCGT workshop "International Workshop:

Origin of Mass and Strong Coupling Gauge Theories (SCGT 06)" in a spirit similar to the previous SCGT meetings. Among the 90 attendants induded Prof. G. 't Hooft and many eminent physicists. In addition to the traditional approaches, recent highlights include the holographic approach to the QCD and other SCGT, which shed new light on the related extra dimensions in terms of deconstruction or Moose/Hidden Local Symmetry. This volume contains 44 reports on the recent progress.

The workshop was financially supported by Daiko Foundation, The Mitsubishi Foundation, the Nagoya University Foundation, a JSPS Grant-in-Aid [(B) 18340059] and a JSPS Award for Eminent Scientists. On behalf of the Organizing Committee, we would like to express our sincere thanks to these organizations for their generous support. We also would like to acknowledge the Research Center for Materials Science, Nagoya University, for their generous offer of the Workshop site at Noyori Memorial Hall of the Center. Special thanks are due to young physicists at Nagoya University for their devoted assistance in preparing the workshop. Finally, we would like to thank Mrs. M. Kitajima for her patient assistance in administrative matters.

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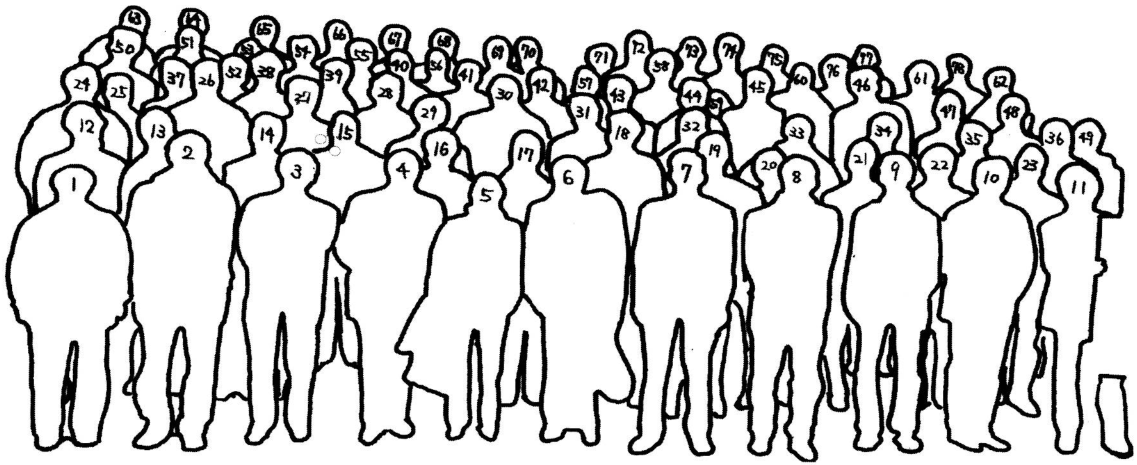

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CONTENTS

THE STRING IN AN EXCITED BARYON

Gerard 't Hooft

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A simple model is discussed in which baryons are represented as pieces of open string connected at one common point. There are two surprises: one is that, in the conformal gauge, the relative lengths of the three arms cannot be kept constant, but are dynamical variables of the theory. The second surprise is that, in the classical limit, the state with the three arms of length not equal to zero is unstable against collapse of one of the arms. After collapse, an arm cannot bounce back into existence. The implications of this finding, which agrees with an earlier report by Sharov, are briefly discussed.

An earlier version of this work was presented at Trento, Italy, Workshop on "Strings and QCD", July 2004.

1. Introduction

Mesons appear to be well-approximated by an effective string model in four dimensions, even if anomalies and lack of super-symmetry cause the spectrum of quantum states to violate unitarity to some extent. Presumably this is because there are no difficulties with classical (open or closed) strings in any number of dimensions, without any super-symmetry. String theory can simply be seen as a crude approximation for mesons, and as such it works reasonably well, although some observed bending of the Regge trajectories at low energies is difficult to reproduce in attempts at an improved treatment of the quantization in such a regime.

It would be very desirable to have an improved effective string model

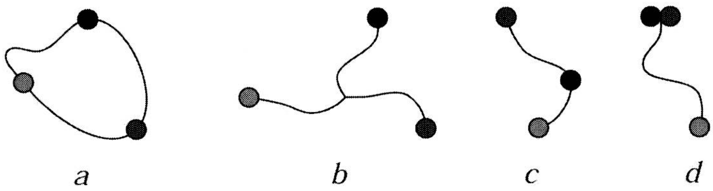

Fig. 1. Four possible string models for baryons. *a*) Three fermions on a closed string; *b*) Our starting point: quarks attached by a single string; *c*) After collapse of one arm; *d*) With two quarks in a $\overline{3}$ bound state.

for QCD even if no refuge can be taken into any supersymmetric deformations of the theory.[1] Such a string model should explain the approximately linear Regge trajectories, and if we can refine it, one might imagine using it as an alternative method to compute spectra and transition amplitudes in mesons and baryons. Ideally, a string model would not serve as a replacement of QCD, but as an elegant computational approach. Since QCD is not supersymmetric, lives in 4 rather than 10 or 26 dimensions, and has massive fermions at the end points of strings (as elementary representations of the color gauge group, rather than massless ones on the interior (which would be in the adjoint representation), one expects quite non-trivial 'corrections' before string theory can describe QCD accurately, but by inspecting the original Veneziano amplitudes for QCD, one nevertheless concludes that string theory, in its basic form, already works in an approximative sense.

The Regge trajectories for baryons appear to have the same slope as the mesonic ones. This can easily be explained if we assume baryons to consist of open strings that tend to have quarks at one end and diquarks at the other. The question asked in this short note is how a classical string model for baryons should be handled.[2,3] In the literature, there appears to be a preference for the Δ model,[4] consisting of a closed string with three fermion-like objects attached to it, see Fig. 1*a*. As closed strings can be handled using existing techniques, this is a natual thing to try.

However, from a physical point of view, the Y-configuration, sketched in Fig. 1*b* appears to be a better representation of the baryons. After all, given three quarks at fixed positions, the Y shape takes less energy. Furthermore, if two of these quarks stay close together, they behave as a diquark and the Regge spectrum (with the *same* slope as the mesons) would be readily explained. However, there turns out to be a good reason why the Y shape is dismissed;[6] we will discuss this, and then ask again whether "Δ" is to be preferred. As will be shown, our conclusion will not be that, but rather an open string with quarks at its end points. The third quark will be allowed to hover in between, attached on this single strand, or tend to stick at one of the ends, leading to a diquark. These will be the most stable configurations, but if completeness is asked for, one has to consider the set of all string configurations, containing open and/or closed pieces, with quarks at three end points.

We considered the exercise of solving the classical string equations for the Y-configuration. After we did this exercise, we found that it has been discussed already by Sharov.[5] The question will be whether we agree with his conclusions. An earlier version of this report appeared in Ref.[7]

2. The three arms

The three arms are described by the coordinate functions $X^{\mu,i}(\sigma,\,\tau)$, where the index i is a label for the arms: $i=1,2$, or 3. At the points $\sigma=0$ (the Torricelli point), the three arms are connected:

$$X^{\mu,1}(0,\,\tau)=X^{\mu,2}(0,\,\tau)=X^{\mu,3}(0,\,\tau)\ . \tag{1}$$

σ is a coordinate along the three arms. It takes values on the segment $[\,0,\,L^i(\tau)\,]$, where as yet we keep the lengths $L^i(\tau)$ unspecified. Indeed, the relative lengths $L^i(\tau)$ of the three arms must be allowed to vary, and the reason for this is displayed in Fig. 2: signals running across the arms and back will have different arrival times, in general, see Fig. 2a. If we wish to fix the coordinates by choosing light cone coordinates, or equivalently, the conformal gauge, Eqs. (3) and (4), this will be important.

The Nambu action is

$$S=-\sum_{i=1}^{3}\int\mathrm{d}\tau\int_0^{L^i(\tau)}\mathrm{d}\sigma\,\sqrt{(\partial_\sigma X^{\mu,i}\cdot\partial_\tau X^{\mu,i})^2-(\partial_\sigma X^{\mu,i})^2(\partial_\tau X^{\lambda,i})^2}\Big)\ . \tag{2}$$

Here, as in the expressions that follow, we assume the usual summation convention for the Lorentz indices $\mu,\ \lambda,\ \ldots$, but not for the branch indices i, where summation, if intended, will always be indicated explicitly. For simplicity, the masses of the quarks at the end points are neglected.

Assuming, in each of the three arms, the classical gauge condition

$$\partial_\sigma X^{\mu,i}\cdot\partial_\tau X^{\mu,i}=0\ ; \tag{3}$$

$$(\partial_\sigma X^{\mu,i})^2=-(\partial_\tau X^{\mu,i})^2\ , \tag{4}$$

Eq. (2) takes the form

$$S = \sum_{i=1}^{3} \int \mathrm{d}\tau \int_0^{L^i(\tau)} \mathrm{d}\sigma \left(\tfrac{1}{2}(\partial_\tau X^{\mu,i})^2 - \tfrac{1}{2}(\partial_\sigma X^{\mu,i})^2 \right) . \tag{5}$$

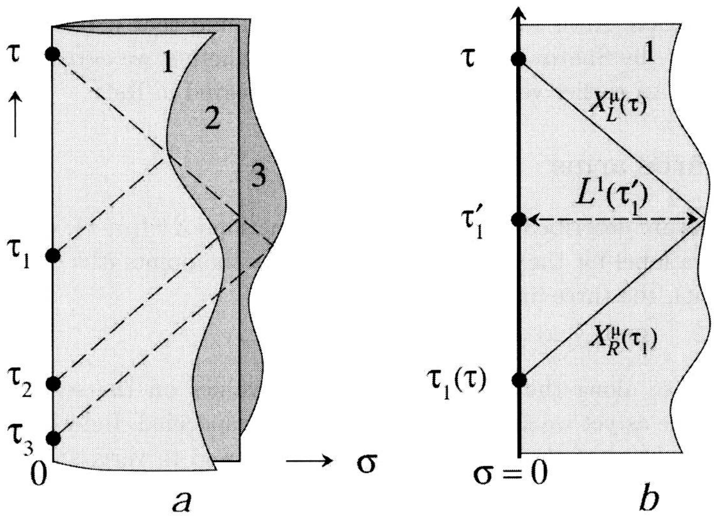

Fig. 2. *a*) The three world sheets. Their relative lengths are dynamical variables. One of the three may be kept fixed. Dashed lines: bouncing waves have differing arrival times. *b*) The variables $L^1(\tau)$ and $\tau_1(\tau_0)$ for branch #1, see text.

3. Boundary conditions

The boundary condition at the Torricelli point can be enforced by two Lagrange multipliers: we add to the action (5)

$$\int \mathrm{d}\tau(\lambda_1^\mu(\tau)(X^{\mu,1}(0,\tau) - X^{\mu,3}(0,\tau)) + \lambda_2^\mu(\tau)(X^{\mu,2}(0,\tau) - X^{\mu,3}(0,\tau)) . \tag{6}$$