Research in Theoretical Nuclear Physics
A Final Technical Report to the Nuclear-Theory Division of the U.S. Department of Energy for the period September 2003-February 2004

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Contents

1 Executive Summary

This report describes research in theoretical nuclear physics carried out in the period September 2003 to February 2004 by Simon Capstick (P.I.), Don Robson (P.I.) and two graduate students: Mr. Alvin Kiswandhi, and Ms. Muslema Pervin. This is the final (close-out) technical report for this grant, which supplements the technical report submitted in August 2003. This research was carried out during part of the third year of the proposal titled *"Research in Theoretical Nuclear Physics"*, and has a strong emphasis on the study of problems relevant to the hadron physics program at Jefferson Laboratory and at other medium-energy laboratories. Of particular importance is our project to study the nature of the multi-quark state (Θ^+) recently discovered in an experiment in Japan, and confirmed in an experiment at Jefferson Laboratory and in other experiments throughout the world. In addition, studies have been made of the confining potentials in conventional and hybrid baryons in the flux-tube model, and their relation to those found in lattice QCD, and of the constraints imposed on microscopic models of the strong decays of hadrons by an anomalously weak meson strong decay.

The research carried out by the graduate students Ms. Muslema Pervin and Mr. Alvin Kiswandhi is progressing well. Ms. Pervin's work on semi-leptonic decays of heavy-quark baryon states can help determine the poorly constrained absolute decay branching fractions for the many observed final states of the ground-state Λ_c baryon, give information about excited final baryon states not accessible in any other way, and provide information about the CKM matrix elements complementary to that found from meson decays. With the excellent progress she has shown on this project so far, she is expected to defend her PhD thesis early in the summer of 2005.

Mr. Kiswandhi joined our group in the Summer of 2002. His work, on theoretical constraints on the determination of the properties of baryon resonances from new high-quality photon-nucleon scattering data in combination with pion-nucleon data, is of fundamental importance to the N^* program in Hall B at Jefferson Laboratory, and has already led to a paper on the model dependence of baryon resonance parameters which has been submitted to Physical Review C.

After many years of research in theoretical nuclear physics carried out at Florida State University, Professor Don Robson retired in July of 2003. Despite his retirement, he remains active in research in support of experiments at F.S.U.'s tandem accelerator facility, and has made important contributions to our research on pentaquark states.

2 List of Personnel

2.1 Principal Investigators

Prof. Simon Capstick

Associate Professor of Physics in the Department of Physics of Florida State University. Supported since 1994 by a grant from the United States Department of Energy (grant No. DE-FG02-86ER40273).

Prof. Don Robson

Full Professor of Physics in the Department of Physics of Florida State University. Supported since 1977 by grants from the United States Department of Energy (currently grant No. DE-FG02-86ER40273). Retired in July 2003 after more than thirty years of active research at Florida State University.

2.2 Graduate Students

Mr. Alvin Kiswandhi

Entering his fourth year as a graduate student in Physics. Started to work with Prof. Capstick in the summer of 2002 on theoretical constraints on baryon resonance analysis. His first paper *"Model Dependence of the Properties of S_{11} Baryon Resonances"* has been published in Physical Review C. Was awarded SURA graduate fellowship in 1994-1995.

Ms. Muslema Pervin

Entering her fifth year as a graduate student in Physics. Started to work with Prof. Capstick in the summer of 2001 on semi-leptonic decays of baryons in the quark model. Recipient of a graduate fellowship to attend the summer 2003 Hampton University Graduate School (HUGS) organized by Hampton University and Jefferson Laboratory (June 2–20, 2003).

State	Quarks	I_z	Decay modes
Θ^-	$dddd\bar{s}$	-2	
Θ^0	$uddd\bar{s}$	-1	nK^0
Θ^+	$uudd\bar{s}$	0	nK^+, pK^0
Θ^{++}	$uuud\bar{s}$	1	pK^+
Θ^{+++}	$uuuu\bar{s}$	2	

Table 1: Quark content, I_z, and strong decay modes of Θ states.

3 Scientific Report

3.1 Interpretation of the Θ^+ as an isotensor pentaquark with weakly decaying partners

(Simon Capstick, P.R. Page, W. Roberts)

Recent analyses of data from experiments using the LEPS at SPring-8 [1], the DIANA bubble chamber at ITEP [2], the CLAS detector at Jefferson Lab [3], and the SAPHIR detector at ELSA [4], point to the existence of a narrow baryon state at around 1540 MeV with strangeness +1, seen by reconstructing the mass of K^+n in various final states. Such a Θ^+ state has a minimal quark content of $uudd\bar{s}$, and so is a manifestly multi-quark state, or pentaquark. The essential problem with understanding this state is to explain its light mass and its narrow width (less than 25 MeV in all experiments, and less than 9 MeV in one experiment [2]), given that it is 100 MeV above the KN threshold. In our recent paper [5] we have examined the consequences of the assumption that this state has isospin 2, which means that the strong decay $\Theta^+ \to K^+n$ is forbidden by isospin symmetry. However, isospin violating decays can proceed through admixtures of $I = 0$ or 1 components in the Θ^+ wave function, and such decays typically have widths of the order or fractions of MeV. Other interpretations are that is a relatively narrow isoscalar, $J^P = 1/2^+$ chiral soliton [6, 7], has a $DD\bar{s}$ structure [8], where D is a tightly bound isoscalar scalar ud diquark, and that it is made up of a light diquark and a $qq\bar{s}$ cluster [9]. The latter allows color-magnetic (hyperfine contact) interactions between the clusters and can explain the low mass of the state.

If this new state has $I = 2$, this implies the existence of a multiplet where the Θ^{++}, Θ^+ and Θ^0 have isospin-violating strong decays, and the Θ^{+++} and Θ^- decay weakly and so are long-lived (see Table 1). The largest mass splitting in the Θ multiplet is expected to be less than 10 MeV. Since the Θ^+ is below $NK\pi$ threshold by about 30 MeV, its isospin partners are also. This precludes the strong decays $\Theta \to NK\pi$, specifically $\Theta^- \not\to n\pi^-K^0$ and $\Theta^{+++} \not\to p\pi^+K^+$, and so these states must decay weakly as indicated in Table 2. A multiplet where the central members (Θ^0, Θ^+ and Θ^{++}) decay strongly, while the outlying members (Θ^{+++} and Θ^-) decay weakly, has no analogue for known mesons and baryons. Production mechanisms for the weakly-decaying states in various reactions are evaluated, and suggestions for favorable experiments at existing facilities are made.

It is conceivable to interpret the isotensor Θ^+ as a ΔK molecule below threshold. However, the Δ is short-lived ($115-125$ MeV wide), making a simple molecular picture unlikely, and the Θ^+ is ~ 190 MeV below the ΔK threshold, which is an atypically large binding energy compared to molecular candidates like the $f_0(980)$ and $a_0(980)$, which are ~ 10 MeV

State	Decay mode		Pairs	State	Decay mode		Pairs
Θ^{+++}	$p\pi^+ l^+ \nu_l$	A	1	Θ^-	$n\pi^-$	E	0
	$p\pi^+\pi^+$	A	1		$n\pi^-\pi^0$	E	1
	$p\pi^+\pi^0 l^+\nu_l$	P	1		$n\pi^-\pi^- l^+\nu_l$	P	1
	$\Delta^{++} l^+\nu_l$	A	0		$\Delta^-\pi^0$	E	0
	$\Delta^{++}\pi^+$	A	0		$\Delta^-\pi^- l^+\nu_l$	P	0
	$\Delta^{++}\pi^0 l^+\nu_l$	P	0		$\Delta^- f_0(600)$	E	0

Table 2: Semi-leptonic and non-leptonic weak decay modes of the Θ^{+++} and Θ^- in order of increasing phase space, where $l = e, \mu$. Also indicated is whether the decay proceeds by single W annihilation (A), exchange (E), or production (P), as well as the number of $q\bar{q}$ pairs that are created by the strong interaction.

below threshold. Furthermore, relating the binding energy of a molecule $1/E_b \sim 2\mu\, r^2_{\text{r.m.s.}}$ to the root mean square separation between the Δ and K, yields $r_{\text{r.m.s.}} \sim 0.5$ fm. This distance is smaller than or similar to the sizes of the constituents, so that the picture of a molecule built from undeformed hadrons is not reasonable.

We conclude that the Θ^+ is best modeled as a pentaquark, as opposed to a loosely bound molecular state. An isotensor pentaquark can only be constructed when each of the quark-pairs are isovector, so that the flavor wave function is also totally symmetric. Assuming that the Θ^+ is the ground-state pentaquark, and that the ground-state has all the quarks and anti-quark in relative S-waves, the spatial wave function is totally symmetric. The Pauli principle and isospin symmetry require the overall fermion wave function to be totally antisymmetric under exchange of the four light quarks, so that the color-quark-spin wave function of the four quarks must be totally antisymmetric.

This implies that the four quarks must be in an antisymmetric representation of the color-spin symmetry group SU(6). This is the $\overline{\mathbf{15}}$ representation of SU(6), which is made up of a color $\overline{\mathbf{6}}$ with spin zero, and a color triplet of spin 1. When combined with the color $\overline{\mathbf{3}}$ anti-quark, a color singlet pentaquark can only have the four quarks combined to a color-triplet with spin 1. This restricts the isotensor pentaquark to $J^P = 1/2^-$ or $3/2^-$.

3.2 Dynamical Models of Pentaquark States

(Simon Capstick, H.J. Lipkin, and D. Robson)

We have calculated the energies of multi-quark configurations $nnnn\bar{s}$, where $n = u, d$ is a light quark, using contact color-magnetic [10] and contact flavor-spin interactions [11] between the quarks (and anti-quark). The former are typical of one-gluon exchange interactions between the quarks, and the latter are typical of chiral one-boson exchange interactions. The lowest energies of such configurations are where the quarks are all in relative S-waves. We have identified the isospin and J^P of the lowest energy states, and work is in progress to establish which of these states are narrow because of a decay selection rule.

3.3 Model Dependence of the Properties of S_{11} Baryon Resonances

(Alvin Kiswandhi, Simon Capstick, S. Dytman)

The properties of baryon resonances are extracted from a complicated process of fitting sophisticated, empirical models to data. This process is made more reliable with high quality data, and with models which incorporate dynamics in a way consistent with theoretical constraints from unitarity and analyticity. Recently a large of amount of scattering data involving baryon resonances has come from experiments, including those at Jefferson Laboratory. Our recent work [12] provides a study of the model dependence of the process of the extraction of baryon resonance properties for a test case where many theoretical details of the model are required, the S_{11} partial wave. The properties of the two lowest N^* resonances in this partial wave are determined using various models of the resonant and non-resonant amplitudes.

This extraction relies on a theoretical description of scattering observables in terms of the properties of baryon resonances, and other parameters describing the non-resonant scattering processes. What is not commonly appreciated is that the results for the extracted properties of baryon resonances depend, sometimes strongly, on the model used to provide this theoretical description. A variety of empirical models are used to fit partial wave amplitudes (the input 'data') for a carefully chosen problem, the S_{11} partial wave and its two most important channels, πN and ηN. This partial wave is interesting because of the physics interest in the S_{11} resonances and the large uncertainty in their properties as reported by the Particle Data Group [13], and since overlapping resonances, multichannel effects, and analyticity constraints are all expected to be important.

Four different resonance models, Carnegie-Mellon Berkeley (CMB) [14, 15, 16], K-matrix [17, 18, 19, 20, 21], and Breit-Wigner with non relativistic and relativistic widths, and two different empirical models for the non resonant amplitude (distant poles and polynomial) are employed. The primary differences among the models come from the way the dynamics of resonance interference, multichannel effects, and non resonant amplitudes are treated. The CMB model with distant poles background satisfies multichannel unitarity and constraints from analyticity, and handles resonance-resonance quantum mechanical interference well. The K-matrix model used here does not satisfy analyticity constraints, and leaves out rescattering dynamics present in the CMB model. The Breit-Wigner models used here satisfy essentially no theoretical constraints. Note, however, that unitary Breit-Wigner models [22] and K-matrix models that satisfy analyticity constraints [17] have been developed.

From Table 3, which shows our results using the distant-poles model of the non resonant amplitudes, it is obvious that the large range of resonance properties given by the Particle Data Group [13] is also found here. This is evidence that much of the uncertainty in the PDG estimates of S_{11} properties comes from model dependence, since we use the same input amplitudes in every fit. Some of the Breit-Wigner models have the best fits to the data, but this is due to the flexibility of these models rather than an ability to describe the underlying dynamics. As a result, the physical properties of the $S_{11}(1650)$ determined with the Breit-Wigner models are very different than with the other models.

At the other extreme, the models with the most theoretical constraints, the CMB and K-matrix models with distant poles background, provide the best consistency with each other and with the CMB fits to a much larger set of reactions [15, 16]. One major result of this work is that the differences between CMB and K-matrix models are not large in a situation where their differences could be expected to be significant. The primary result is

	model	CMB	K matrix	$\mathrm{BW}_{\mathrm{n.r.}}$	$\mathrm{BW}_{\mathrm{rel}}$	CMB all πN	CMB all πN, γN
$S_{11}(1535)$	Mass (MeV)	1539	1533	1554	1560	1547±3	1539±5
	Width (MeV)	138	116	140	145	131±19	122±20
	$B_{\pi N}$	28%	34%	81%	74%	34±4%	39±5%
$S_{11}(1650)$	Mass (MeV)	1681	1685	1609	1626	1690±12	1684±15
	Width (MeV)	142	190	135	140	227±40	227±58
	$B_{\pi N}$	80%	77%	90%	87%	75±3%	75±3
	χ^2/N	3.8	3.7	3.3	1.9	3.6	5.6

Table 3: Results for resonance parameters from fits to the T matrix elements for $\pi N \to \pi N$, ηN in the S_{11} partial wave, using CMB, K-matrix, and Breit-Wigner (BW) models. The next to last column shows the results of a fit including $\pi N \to \pi N$, ηN , ρN, $\pi \Delta$, σN and πN^* partial wave amplitudes [15]. The last column shows results for a fit of the πN data and $\gamma N \to \pi N$, ηN data [16]. Non-resonant contributions to the T matrix are described in terms of distant poles in all cases. Only the branching fraction to πN is given, since $B_{\eta N} = 1 - B_{\pi N}$. The last row gives the χ^2 per data point of each fit.

that even in a small multi-channel problem, dynamics are important. Since Breit-Wigner models have very few theoretical constraints, ad-hoc parameters are required to fit real data such as those of the two-channel problem studied here. As a result, for these models the resonance parameters are very different than those derived using more theoretically correct models.

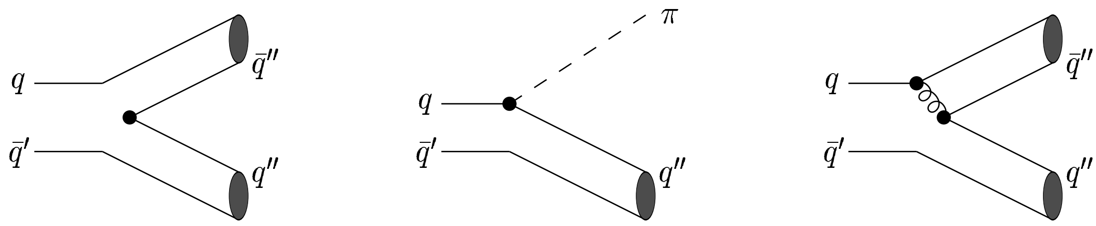
3.4 The anomalous suppression of $\pi_2(1670) \to b_1\pi$

(Simon Capstick, P.R. Page)

We show that current analyses of experimental data indicate that the strong decay mode $\pi_2 \to b_1\pi$ is anomalously small, which acts as a powerful discriminator for and against various decay models. For example, in non-relativistic quark-pair-creation models, where OZI-allowed meson decay processes are modeled by an initial $q\bar{q}'$ pair decaying to the two pairs $q\bar{q}''$ and $q''\bar{q}'$ (see Fig. 1), a simple selection rule arises when all the mesons have quark-spin $S = 0$. If the $q''\bar{q}''$ pair are created with quark-spin $S_{\mathrm{pair}} = 1$, then conservation of quark-spin implies that the amplitude is zero.

This constraints imposed by this particular decay are unique. In the quark model, conventional mesons with $S = 0$ have $J^{PC} = 0^{-+},\ 1^{+-},\ 2^{-+},\ 3^{+-},\ 4^{-+},\ 5^{+-}, \ldots$, of which only states corresponding to the first three J^{PC} have been established experimentally [13]. The isovector resonances with these three J^{PC} and in their radial ground states are π, b_1 and π_2, respectively. The only kinematically allowed decay involving these three $S = 0$ resonances is $\pi_2 \to b_1\pi$. Moreover, all other kinematically allowed decays involving π, b_1, π_2, and their isoscalar partners, are forbidden by the quantum numbers conserved by the strong interaction.

This selection rule establishes that the phenomenologically successful pair-creation model for light-light mesons (the $^3P_0$ model) [23], and the chromo-electric string-breaking model



$^3P_0$, $^3S_1$, $^3D_1$ models π exchange model Gluon exchange

Figure 1: The OZI allowed decay of an initial meson to two final mesons in various models.

($^3S_1$ or $^3D_1$ model) are consistent with the experimental decay width of $\pi_2 \to b_1\pi$. By similar arguments we show that instantons [24], and the lowest order one-boson emission model, which has successfully been applied to the decay of heavy-light mesons [25, 26], are also consistent with the small width of $\pi_2 \to b_1\pi$. For mesons made up only of heavy quarks, we show that the selection rule is exact to all orders of Quantum Chromodynamics perturbation theory.

Models and effects that violate this selection rule, such as higher order one-boson emission models, as well as mixing with other Fock states, may be constrained by the small $\pi_2 \to b_1\pi$ decay. This can provide a viability check on newly proposed decay mechanisms. Higher order contributions in one-boson emission models contain terms that are not of the form $\boldsymbol{\sigma}_q \cdot \mathbf{p}$, which violate the selection rule. An example is interactions where *both* a pseudoscalar boson is emitted, *and* a particle is exchanged between the quark and anti-quark in the initial meson, which are introduced in one-pseudoscalar-boson emission models to cure problems with the lowest order contribution [25, 26].

Consistency with the small decay branch for $\pi_2 \to b_1\pi$ can also provide a viability check on proposed decay mechanisms. An example, depicted in Fig. 1, is where there is a single gluon exchanged between a quark in the decaying hadron and the vertex at which the quark pair is created. This one-gluon exchange quark pair creation decay mechanism violates the selection rule, since it involves both Coulomb and transverse interactions. The former has a simple $\boldsymbol{\sigma} \cdot \mathbf{p}$ pair creation operator, but the latter has spin vector operators at *both* interaction vertices of the gluon, giving rise to a violation of the selection rule. However, it is found to be sub-dominant relative to the $^3P_0$ model [27], so that it is not expected to be constrained by $\pi_2 \to b_1\pi$. If appreciable strength for $\pi_2(1670) \to b_1(1235)\,\pi$, inconsistent with experiment, is predicted by either higher order terms present in the one-boson emission decay mechanism, or by the one-gluon exchange pair creation decay mechanism, one of these decay models could be ruled out. This could distinguish between the OBE and one-gluon exchange models of the coarse features of the light baryon spectrum.

Further breaking of this selection rule can arise from mixing with other Fock states. The mixing of mesons participating in the decay with non-meson Fock states is constrained by the experimentally measured $\pi_2 \to b_1\pi$ width. Examples are mixing between the $S = 0$ meson π_2 and the $S = 1$ hybrid π_2 meson expected nearby in mass, and non-mesonic Fock states in the pseudo-Goldstone boson π.

3.5 Semileptonic Decays of Baryons

(Muslema Pervin, Simon Capstick, and W. Roberts)

Semileptonic decays of mesons have been extensively studied in models of hadron struc-

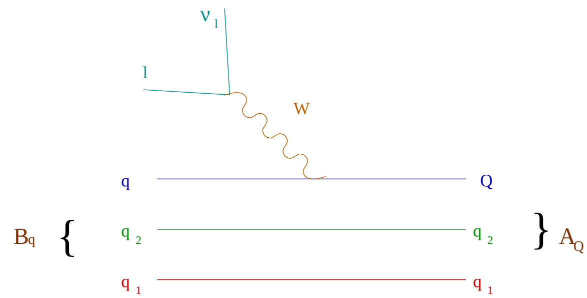


Figure 2: Baryon semileptonic decay $A_Q \to B_q l \nu_l$ (time runs from right to left).

ture because of their relationship to the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements, which are very important because of their relation to CP violation in weak decays. They cannot be extracted from semileptonic decay data without knowledge of the hadronic matrix elements of the weak current, which in turn requires knowledge of the structure of the hadrons involved. Quark model calculations of the B and D-meson form factors, and rates for decays of pseudoscalar mesons to both pseudoscalar and vector mesons [28, 29], were the foundation for calculations involving heavy quark effective theory [30].

Semileptonic decays of baryons have the potential to provide complementary information about the CKM matrix elements, and also to yield unique information about the structure of excited baryons. Decays of ground-state Λ_Q and Σ_Q baryons to excited baryons can explore properties of excited states not accessible in electromagnetic production experiments. In addition, a quark model estimate of the rates for Λ_c to decay to ground and excited hyperon states can help provide the absolute scale for charmed baryon decays [13].

Prior work on the exclusive semileptonic decays of baryons [31] has largely been limited to transitions involving ground states, or in one case from a $J^P = 1/2^+$ ground state to a $J^P = 3/2^+$ excited final state for $\Lambda_b \to \Lambda_c$ decays [32]. Our calculation will ultimately evaluate all of the form factors for the decay channels $\Lambda_b \to \Lambda_c$, $\Lambda_c \to \Lambda$, $\Sigma_b \to \Sigma_c$, $\Sigma_c \to \Sigma$, $\Omega_b \to \Omega_c$, $\Omega_c \to \Omega$, $\Lambda_b \to N$, $\Sigma_b \to \Delta$, $\Sigma_c \to N$, neutron beta decay, etc. Final state baryons will include all possible excited states up to and including the lowest-lying positive-parity excitations, which includes states with $J^P = 1/2^\pm$, $3/2^\pm$, $5/2^\pm$, and $7/2^+$. This requires construction of the spatial-spin part of the non relativistic quark model wave functions, different in the Λ and Σ states. These wave functions will then be used to calculate the hadronic matrix elements of the vector and axial-vector weak currents on the left hand side of the equations

$$\langle \Lambda_q(p', s')|V_\mu|\Lambda_Q(p,s)\rangle = \overline{u}(p', s')\left[F_1(q^2)\gamma_\mu + F_2(q^2)\frac{p_\mu}{m_Q} + F_3(q^2)\frac{p'_\mu}{m_q}\right]u(p,s)$$

$$\langle \Lambda_q(p', s')|A_\mu|\Lambda_Q(p,s)\rangle = \overline{u}(p', s')\left[G_1(q^2)\gamma_\mu + G_2(q^2)\frac{p_\mu}{m_Q} + G_3(q^2)\frac{p'_\mu}{m_q}\right]\gamma_5 u(p,s),$$

which yield the form factors F_i and G_i. Decay rates are calculated by contracting a hadronic tensor, proportional to these form factors, with a well known leptonic tensor.

We have made significant progress toward these goals. We have reproduced the calculation in Ref. [28, 29] of the form factors for the semileptonic decays of pseudoscalar mesons to both pseudoscalar and vector mesons, using a harmonic oscillator basis, and have calculated the pseudoscalar to pseudoscalar meson decay form factors using the Sturmion basis. For baryon semileptonic decay, we have obtained the general form of the hadronic tensor for $J^P = \frac{1}{2}^+ \rightarrow \frac{1}{2}^\pm, \frac{3}{2}^\pm, \frac{5}{2}^\pm$ decays by using the HIP (High energy physics Instruction Package) package of *Mathematica*.

Wave functions have been constructed using the harmonic oscillator basis up to and including the second oscillator level, for Λ states which can be connected to the initial $\Lambda_Q 1/2^+$ ground state, and similarly for Σ states which can couple to the initial ground state $\Sigma_Q 1/2^+$. Using harmonic oscillator wave functions, we have calculated form factors for $\Lambda_b\frac{1}{2}^+ \rightarrow \Lambda_c$ decays to the $\Lambda_c\frac{1}{2}^+$ ground state, a $\Lambda_c\frac{1}{2}^+$ excited state, and $\Lambda_c\frac{1}{2}^-$, $\Lambda_c\frac{3}{2}^+$, and $\Lambda_c\frac{3}{2}^-$ excited states, as well as form factors for $\Sigma_b\frac{1}{2}^+ \rightarrow \Sigma_c$ decays to the $\Sigma_c\frac{1}{2}^+$ ground state, a $\Sigma_c\frac{1}{2}^+$ excited state, and a $\Sigma_c\frac{1}{2}^-$ excited state.

Use of the harmonic oscillator basis yields form factors which fall off like Gaussians in momentum space at large momentum, whereas hadron form factors extracted from experiments generally fall off like inverse powers of $1 + Q^2/\Lambda^2$. Use of a different basis in momentum space, known as the Sturmion basis, can give the correct behavior of the form factors at high momentum [33]. Sturmion basis functions are of the form

$$\psi_{nLm}(\mathbf{p}) = N_{nL}\frac{(\mathbf{p}/\alpha)^L}{(\mathbf{p}^2/\alpha^2+1)^{L+2}}(-i)^L P_n^{(L+3/2,L+1/2)}\left(\frac{\mathbf{p}^2-\alpha^2}{\mathbf{p}^2+\alpha^2}\right)Y_{Lm}(\mathbf{p}),$$

where N_{nL} is a normalization factor, and the associated Laguerre polynomial $P_n^{(L+3/2,L+1/2)}$ is a Jacobi polynomial. Using this Sturmion basis we have calculated form factors for essentially all of the decays mentioned above.

3.6 Flux-tube model interpretation of lattice QCD results for baryon potentials

(Simon Capstick, P.R. Page)

Recent calculations of the three-quark potential in SU(3) lattice QCD [34, 35], with static (infinitely heavy) quarks QQQ, convincingly demonstrate that the potential is, at larger separations, proportional to the length of the components of a Y-shaped string, rather than to the sum of the inter-quark distances (the Δ Ansatz). This is the behavior expected from the flux-tube model [36]. In addition, a simultaneous study of the ground and first excited state potential of the glue in SU(3) lattice QCD [37] shows that the first excited state of the glue lies between 1.2 and 0.68 GeV for Y-shaped strings of total length between 0.27 and 1.37 fm.

Our previous work on baryons with excited glue, or hybrid baryons [38, 39], used the flux-tube model to estimate the masses and quantum numbers of the lowest-lying states made up of light quarks (N and Δ hybrid baryons). In this model, the gluonic degrees of freedom are modeled by lines of color-electric flux which meet at a junction in a Y-shaped configuration, as motivated by strong-coupling Hamiltonian lattice gauge theory. These lines are discretized by a number of beads, and the zero point energy and first excited state energy of the Y-shaped string are evaluated numerically. These energies form potentials in which the quarks move, in conventional and hybrid baryons respectively, using an adiabatic approximation to separate the dynamics of the gluonic and quark degrees of freedom.

Recent lattice QCD results [34, 35] for the ground state and first excited state energy of the glue in the presence of three static quarks are interpreted in terms of our flux-tube

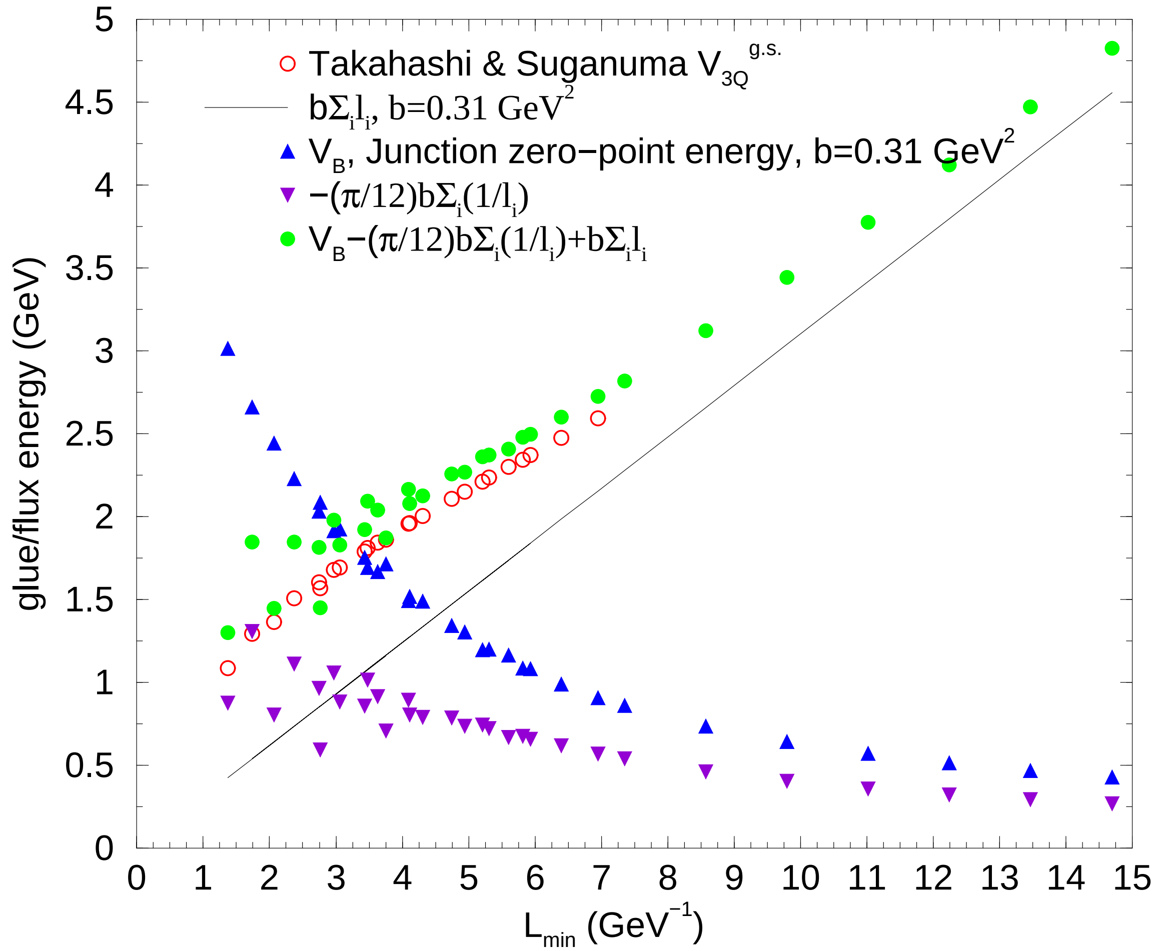


Figure 3: Comparison of lattice results for the ground state energy of the glue in the presence of three static quarks (open circles) to that calculated in the flux-tube model of Ref. [39] (filled circles), plotted against the minimum length $L_{\rm min} = b\sum_i l_i$ of the Y-shaped string connecting the quarks to the junction. Also shown are the static energy of the string (solid line), the junction zero-point energy (triangles), and the Lüscher term (inverted triangles).

model. Figure 3 shows that a good description of the ground state energy is provided in this model by the zero-point energy of the junction between the segments of length l_i of a Y-shaped string, the zero-point energies of the three segments of this string, given by a Lüscher [40] term $-(\pi/12)\sum_i(1/l_i)$, and the static energy $b\sum_i l_i$ associated with the total length of the string, where b is the string tension. In particular, a color-Coulomb term is not needed down to inter-quark distances of the order of 0.15 fm. The energy of the first excited state of the glue in this model has been compared to that of the lattice results, and consequences for the masses of hybrid baryons determined. A paper on this work is currently in preparation.

3.7 Multistep processes in the ^{12}C(^{6}Li,d) stripping reaction

(Don Robson, N. Keeley, *et al.*)

The results of extensive coupled-reaction-channel calculations are compared with the cross section and new analyzing power data for the ^{12}C(^{6}Li,d)^{16}O reaction leading to the

0.0-MeV 0^+, 6.13-MeV 3^-, 6.92-MeV 2^+, 8.87-MeV 2^-, and 10.35-MeV 4^+ states of ^{16}O at ^{6}Li bombarding energies of 34 and 50 MeV. All the analyzing power data at both energies and all the cross section data at 50 MeV, with the exception of that for the ^{12}C(^{6}Li,d)^{16}O transition to the 0.0-MeV 0^+ state of ^{16}O are presented here for the first time. These results suggest that there are significant multistep contributions to transfers leading to the 0^+ and 3^- states, while those leading to the 2^+ and 4^+ states may be reasonably well described by simple direct transfer. The importance of multistep effects is found to increase with increasing bombarding energy. This work was published in Physical Review C (April 2003), but not included on in our previous technical progress report.

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Presentations at Meetings

1. S. Capstick, "Nucleon excited states: theoretical issues?", invited talk given at Jefferson Laboratory Physics Advisory Committee (25) N* Mini-Workshop, Williamsburg, VA, January 2004.

2. S. Capstick, "Interpretation of the Theta+ as a true pentaquark", invited talk given at the Penta-Quark 2003 Workshop, Jefferson Lab, Newport News, VA, November 2003.

3. S. Capstick, "The Excitement about pentaquarks", Department of Physics colloquium, University of Guelph, Guelph ON, Canada, September 2003.