CPC(HEP & NP), 2010, **34**(9): 1428–1432 **Chinese Physics C** Vol. 34, No. 9, Sep., 2010

K^-p scattering and hyperon excitations in a chiral quark model*

ZHONG Xian-Hui(钟显辉)[1,3;1)] ZHAO Qiang(赵强)[2,3;2)]

[1] Department of Physics, Hunan Normal University, Changsha 410081, China
[2] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
[3] Theoretical Physics Center for Science Facilities, Chinese Academy of Sciences, Beijing 100049, China

Abstract A chiral quark-model approach is employed to study the $\bar{K}N$ scattering at low energies. The processes of $K^-p \to \Sigma^0\pi^0$, $\Lambda\pi^0$ and $\bar{K}^0n$ at $P_K \lesssim 800$ MeV/c (i.e. the center mass energy $W \lesssim 1.7$ GeV) are investigated. The analysis shows that the $\Lambda(1405)S_{01}$ dominates the processes $K^-p \to \Sigma^0\pi^0$, $\bar{K}^0n$ in the energy region considered here. Around $P_K \simeq 400$ MeV/c, the $\Lambda(1520)D_{03}$ is responsible for a strong resonant peak in the cross section of $K^-p \to \Sigma^0\pi^0$ and $\bar{K}^0n$. To reproduce the data, an unexpectedly large coupling for $\Lambda(1520)D_{03}$ to KN is needed. In contrast, the coupling for $\Lambda(1670)S_{01}$ to KN appears to be weak, which could be due to configuration mixings between $\Lambda(1405)S_{01}$ and $\Lambda(1670)S_{01}$. By analyzing $K^-p \to \Lambda\pi^0$, evidences for two low mass S-wave states, $\Sigma(1480)S_{11}$ and $\Sigma(1560)S_{11}$, seem to be available. With these two states, the reaction $K^-p \to \bar{K}^0n$ can also be described well. However, it is difficult to understand the low masses of $\Sigma(1480)S_{11}$ and $\Sigma(1560)S_{11}$. The s-channel amplitudes for $K^-p \to \Lambda\pi^0$ are also larger than the naive quark model expectations. The non-resonant background contributions, i.e. t-channel and/or u-channel, also play important roles in the explanation of the angular distributions due to amplitude interferences.

Key words strange resonance, quark model, meson-baryon interaction

PACS 25.80.Nv, 13.75.Jz, 12.39.Jh

1 Introduction

In the literature, many experimental and theoretical efforts have been devoted to understanding the nature of the low-lying Λ and Σ resonances, i.e. hyperons. However, the properties of most resonances are still controversial. For example, in the Λ spectrum it is still undetermined whether the $\Lambda(1405)S_{01}$, $\Lambda(1670)S_{01}$ and $\Lambda(1520)D_{03}$, are genuine qqq states or have components beyond the qqq scenario, such as multi-quark structure, though their J^P are determined [1–14]. In the Σ spectrum, although a lot of states, such as $\Sigma(1480)$bumps, $\Sigma(1560)$bumps, $\Sigma(1670)$bumps and $\Sigma(1690)$bumps, have been listed by the Particle Data Group (PDG) [15], they are not established at all. Their quantum numbers, structures, and resonance parameters are still unknown. How to clarify these issues and make a contact with experimental observables are still an open question in theory.

Recently, the high-precision data for reactions $K^-p \to \Sigma^0\pi^0$, $\Lambda\pi^0$ and $\bar{K}^0n$ at eight momentum beams between 514 and 750 MeV/c are reported [16, 17]. It provides us a good opportunity to study the properties of these low-lying Λ and Σ resonances. In this proceeding, we will report our progress on the investigation of the K^-p reactions in a chiral quark model. In this model an effective chiral Lagrangian is introduced to account for the quark-pseudoscalar-meson coupling. Since the quark-meson coupling is invariant under the chiral transformation, some of the low-energy properties of QCD are retained. The chiral quark model has been well developed and widely applied to meson photoproduction reactions [18–26]. Its recent extension to describe the process of πN and KN scattering [27, 28] and investigate the strong

---

Received 19 January 2010

* Supported by National Natural Science Foundation of China (10675131, 10775145) and Chinese Academy of Sciences (KJCX3-SYW-N2)

1) E-mail: zhongxh@ihep.ac.cn

2) E-mail: zhaoq@ihep.ac.cn

decays of charmed hadrons [29] also turns out to be successful and inspiring.

As follows, we first give a brief introduction to the chiral quark model framework. In Sec. 3, we present the numerical results for $\mathrm{K^-p\to\Sigma^0\pi^0}$, $\Lambda\pi^0$ and $\mathrm{\bar{K}^0n}$ in parallel with the experimental data. A summary is given in Sec. 4.

2 Framework

In the chiral quark model, the quark-pseudoscalar-meson coupling at tree level is described by [25, 26]

$$H_{\rm m}=\sum_j \frac{1}{f_{\rm m}}\bar{\psi}_j\gamma^j_\mu\gamma^j_5\psi_j\vec{\tau}\cdot\partial^\mu\vec{\phi}_{\rm m}, \tag{1}$$

and the vector meson-quark coupling is given by

$$H_{\rm V}=\bar{\psi}_j\left(a\gamma^\nu+\frac{ib\sigma^{\nu\lambda}q_\lambda}{2m_{\rm q}}\right)V_\nu\psi_j\ , \tag{2}$$

where ψ_j represents the j-th quark field in a baryon, and $f_{\rm m}$ is the meson's decay constant. The pseudoscalar-meson octet $\phi_{\rm m}$ is written as

$$\phi_{\rm m}=\begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{6}}\eta & \pi^+ & \mathrm{K}^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0+\frac{1}{\sqrt{6}}\eta & \mathrm{K}^0 \\ \mathrm{K}^- & \bar{\mathrm{K}}^0 & -\sqrt{\frac{2}{3}}\eta \end{pmatrix}, \tag{3}$$

and the vector-meson octet V is given by

$$V=\begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0+\frac{1}{\sqrt{2}}\omega & \rho^+ & \mathrm{K}^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0+\frac{1}{\sqrt{2}}\omega & \mathrm{K}^{*0} \\ \mathrm{K}^{*-} & \bar{\mathrm{K}}^{*0} & \phi \end{pmatrix}, \tag{4}$$

where the constants a and b are the vector and tensor coupling constants. They are treated as free parameters in this work.

The s and u channel transition amplitudes are determined by

$$\mathcal{M}_{\rm s} = \sum_j\langle N_{\rm f}|H_\pi|N_j\rangle\langle N_j|\frac{1}{E_i+\omega_{\rm K}-E_j}H_{\rm K}|N_i\rangle, \tag{5}$$

$$\mathcal{M}_{\rm u} = \sum_j\langle N_{\rm f}|H_{\rm K}\frac{1}{E_i-\omega_\pi-E_j}|N_j\rangle\langle N_j|H_\pi|N_i\rangle, \tag{6}$$

where $\omega_{\rm K}$ is the energy of the incoming $\mathrm{K^-}$-meson. $H_{\rm K}$ and H_π are the standard quark-meson couplings at tree level described by Eq. (2). $|N_i\rangle$, $|N_j\rangle$ and $|N_{\rm f}\rangle$ stand for the initial, intermediate and final state baryons, respectively, and their corresponding energies are E_i, E_j and $E_{\rm f}$, which are the eigenvalues of the NRCQM Hamiltonian $\hat{H}$ [1, 30]. The s and u channel transition amplitudes have been worked out in the harmonic oscillator basis in Refs. [27, 28].

For the t-channel, we considered the vector meson K^* and scalar meson κ exchange in the reactions. The following effective Lagrangian is adopted for the pseudoscalar-vector meson coupling [31, 32]:

$$H_{\rm PPV}=-\mathrm{i}G_{\rm V}\mathrm{Tr}([\phi_{\rm m},\partial_\mu\phi_{\rm m}]V^\mu). \tag{7}$$

The amplitudes have been derived in Ref. [28].

The amplitudes in terms of the harmonic oscillator principle quantum number n are the sum of a set of $SU(6)$ multiplets with the same n. For example, in the $n=1$ shell there are four contributing Λ resonances, i.e. $\Lambda(1405)S_{01}$, $\Lambda(1520)D_{03}$, $\Lambda(1670)S_{01}$ and $\Lambda(1690)D_{03}$, and seven Σ resonances, i.e. $[70,^2 8]S_{11}$, $[70,^2 8]D_{13}$, $[70,^2 10]S_{11}$, $[70,^2 10]D_{13}$, $[70,^4 8]S_{11}$, $[70,^4 8]D_{13}$ and $[70,^4 8]D_{15}$. To see the contributions of individual resonances, we need to separate out the single-resonance-excitation amplitudes within each principle number n in the s-channel.

Taking into account the width effects of the resonances, the resonance transition amplitudes of the s-channel can be generally expressed as [26, 27]

$$\mathcal{M}^{\rm s}_{\rm R}=\frac{2M_{\rm R}}{s-M^2_{\rm R}+\mathrm{i}M_{\rm R}\Gamma_{\rm R}}\mathcal{O}_{\rm R}\mathrm{e}^{-(\boldsymbol{k}^2+\boldsymbol{q}^2)/6\alpha^2}, \tag{8}$$

In Eq. (8), $\mathcal{O}_{\rm R}$ is the separated operators for individual resonances in the s-channel. The detail of extracting $\mathcal{O}_{\rm R}$ can be found in our recent work [28].

3 Results

In Figs. 1 and 2, the differential cross sections and the total cross sections for $\mathrm{K^-p\to\Sigma^0\pi^0}$, $\Lambda\pi^0$ and $\mathrm{\bar{K}^0n}$ at low energy region are reproduced successfully.

The resonance parameters used in present work are listed in Table 1. They are fitted to the differential cross sections [16, 17], and agree with the PDG values within the experimental uncertainties [15].

In $\mathrm{K^-p\to\Lambda\pi^0}$, two low-mass S-wave resonances, $\Sigma(1480)$ and $\Sigma(1560)$, seem to be needed to reproduce the data. Further evidence of $\Sigma(1480)$ could be found in the $\mathrm{K^-p\to\bar{K}^0n}$. It should be pointed out that to reproduce the data for $\mathrm{K^-p\to\Lambda\pi^0}$, larger amplitudes of the s-channel are used. This is consistent with the analysis by Oller et al. [9, 10]. Apart from the $\mathrm{K^-p}$ scattering, obvious evidence of $\Sigma(1480)$ is also confirmed in a recent study of $\mathrm{pp\to pK^+Y^*}$ [33]. Furthermore, the low mass and broad width S-wave Σ state required here is in good agreement with Ref. [34], where a S-wave Σ state with a mass of 1446 MeV and width of 343 MeV is suggested as well. More recently, Wu, Dulat and Zou find some evidence for a

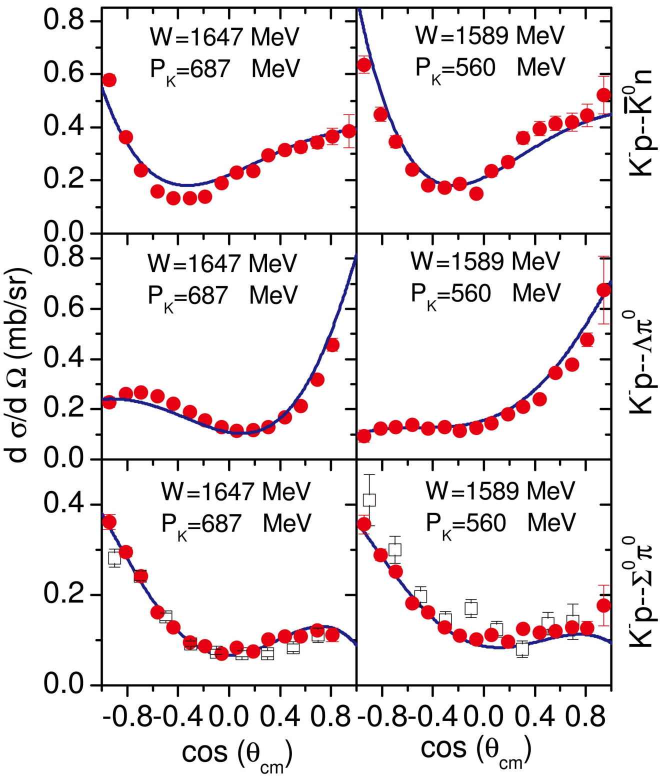

Fig. 1. Differential cross sections for $K^-p \rightarrow \Sigma^0\pi^0$, $\Lambda\pi^0$ and $\bar{K}^0n$. The data are from Refs. [16, 17].

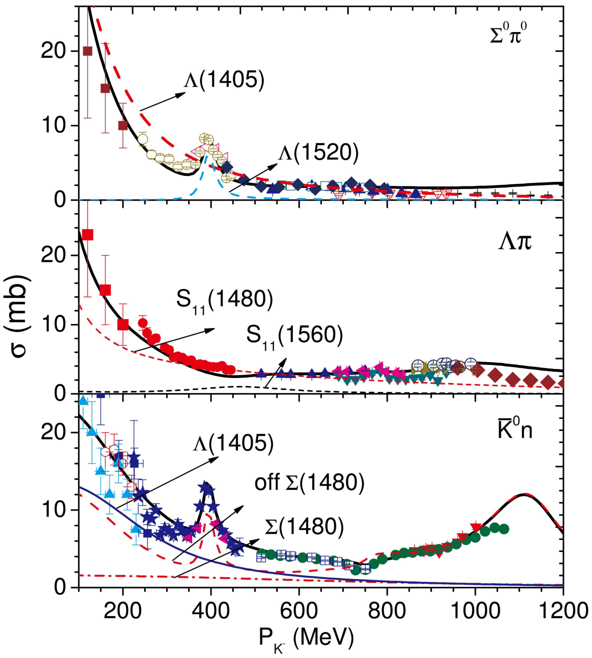

Fig. 2. Total cross sections for $K^-p \rightarrow \bar{K}^0n$, $\Lambda\pi^0$, $\Sigma^0\pi^0$, respectively. The solid curves are the full model calculations. 1) Data for $K^-p \rightarrow \bar{K}^0n$ are from Refs. [17] (open squares), [36] (solid circles), [37] (left-triangles), [38] (down-triangles), [39] (stars), [40] (up-triangles), [41] (open circles), [42] (solid squares). 2) Data for $K^-p \rightarrow \Lambda\pi^0$ are from Refs. [43] (open squares), [36] (solid circles), [44] (left-triangles), [38] (right-triangles), [45] (down-triangles), [17] (up-triangles), [46] (open circles), [40] (solid squares), [47] (solid diamonds). 3) Data for $K^-p \rightarrow \Sigma^0\pi^0$ are from Refs. [45] (down-triangles), [48] (solid circles), [43] (solid diamonds), [37] (left-triangles), [49] (up-triangles), [16] (open squares), and [40] (solid squares).

very low mass (M∼ 1385 MeV) *S*-wave state with a broad width in the old data for $K^-p \to \Lambda\pi^+\pi^-$ [35]. But their mass is much less than 1480 MeV.

The $\Lambda(1405)S_{01}$, which was reported previously in our recent work [28], is also confirmed in $K^-p \to \bar{K}^0 n$. The fitted mass is ∼ 1420 MeV, which is about 10 MeV larger than the upper limit of the PDG-suggested value [15].

Both $K^-p \to \bar{K}^0 n$ and $K^-p \to \Sigma^0\pi^0$ reactions require a much larger contribution from $\Lambda(1520)$ than the quark model predictions. In contrast, we find that the data favor a much smaller contribution from $\Lambda(1670)$ than the quark model prediction. The weak coupling of $S_{01}(1670)$ to $\bar{K}N$ is also suggested by Oset et al. [13] in their UχPT model.

In $K^-p \to \Sigma^0\pi^0$, $\Lambda\pi^0$ and $\bar{K}^0 n$, the non-resonant backgrounds, u and t channels, play very important roles. In the u-channel, the contributions mainly come from the $n=0$ shell nucleon or Δ pole. And in the t channel, the contributions mainly come from the vector mesons (K^*, ρ) and scalar mesons (κ, $a_0(980)$) exchanges.

Table 1. The fitted Breit-Wigner masses M (in MeV) and widths Γ (in MeV) for the s-channel resonances compared with the data. We note that $\Sigma(1480)$, $\Sigma(1560)$ and $\Sigma(1670)$ are the unestablished states which are listed as bumps in PDG [15].

	$l_{I,2J}$	M	Γ	$M_{\rm exp}$	$\Gamma_{\rm exp}$
$[\mathbf{70},^2 1]$	S_{01}	1425	80	1406 ± 4	50 ± 2
	D_{03}	1520	13	1520 ± 1	16 ± 1
$[\mathbf{70},^2 10]$	S_{11}	1790	160	1765 ± 35	$60\sim160$
	D_{13}	1780	80	?	?
$[\mathbf{70},^2 8]$	S_{01}	1678	40	1670 ± 10	$25\sim50$
	D_{03}	1690	60	1690 ± 5	60 ± 10
	S_{11}	1550	110	$\Sigma(1560)$	$10\sim110$
	D_{13}	1680	70	1675 ± 10	60 ± 20
$[\mathbf{70},^4 8]$	S_{11}	1460	340	$\Sigma(1480)$	$10\sim100$
	D_{13}	1690	80	$\Sigma(1670)$	30 ± 120
	D_{15}	1775	120	1775 ± 5	120 ± 15
$[\mathbf{56},^2 8]$	P_{01}	1630	140	1630 ± 70	150 ± 100
	P_{11}	1660	250	1660 ± 30	$40\sim200$

In the quark model framework, the u channel allows transitions that the initial and final state mesons can be coupled to the same quark or different quarks, while the s-channel can only occur via transitions that the initial and final state mesons are coupled to different quarks. This explains the importance of the u-channel contributions as a unique feature in the K^-p scattering. In comparison with the UχPT, the agreement implies some similarity of the coupling structure at leading order. The important role of u channel in these reactions is also addressed in the BχPT [14] and UχPT studies [8, 9].

The $\Lambda(1405)S_{01}$ is the major contributor of the *S*-wave amplitude in the reactions $K^-p \to \Sigma^0\pi^0$ and $\bar{K}^0 n$ in the low-energy region. In contrast, the $\Sigma(1480)S_{11}$ seems to be the major contributor of the *S*-wave amplitude in $K^-p \to \Lambda\pi^0$ according to our analysis. Around $P_K = 400$ MeV/c, the $\Lambda(1520)D_{03}$ is responsible for the strong resonant peak in the total cross sections of these two reactions. Around $P_K = 700 \sim 800$ MeV/c, the differential cross sections are sensitive to the $\Lambda(1670)S_{01}$.

4 Summary

In this proceeding, we report our preliminary results for the K^-p scattering within a chiral quark model. We find that the non-resonant backgrounds, u and/or t channels, play very important roles in the K^-p scatterings. The $\Lambda(1405)$ seems to have a mass ~ 1420 MeV, which is about 10 MeV larger than the PDG value. It is found that the $\Lambda(1670)S_{01}$ has very weaker couplings to KN, which may be explained by the configuration mixings between $\Lambda(1405)S_{01}$ and $\Lambda(1670)S_{01}$ as suggested in our previous work [28]. However $\Lambda(1520)D_{03}$ has unexpected strong couplings to KN, which is difficult to be explained within the naive quark model.

The data for $K^-p \to \Lambda\pi^0$ seem to favor two low-mass states, $\Sigma(1480)$ and $\Sigma(1560)$, in the reactions. The analysis of the process $K^-p \to \bar{K}^0 n$ seems to support this conclusion as well. However, there are several puzzles should be studied further: i) why the masses of $\Sigma(1480)$ and $\Sigma(1560)$ are much smaller than the quark model predictions? ii) why the amplitudes of the s channel in $K^-p \to \Lambda\pi^0$ are much larger than the quark model predictions? Our final results will be reported in a forthcoming work.

References

1 Isgur N, Karl G. Phys. Rev. D, 1978, **18**: 4187

2 Capstick S, Isgur N. Phys. Rev. D, 1986, **34**: 2809

3 Loring U, Metsch B C, Petry H R. Eur. Phys. J. A, 2001, **10**: 447

4 Dalitz R H, Tuan S F. Phys. Rev. Lett. 1959, **2**: 425 ; Annals Phys. 1960, **10**: 307

5 Oset E, Ramos A. Nucl. Phys. A 1998, **635**: 99

6 Oller J A, Meissner U G. Phys. Lett. B, 2001, **500**: 263

7 Jido D, Oller J A, Oset E, Ramos A, Meissner U G. Nucl. Phys. A, 2003, **725**: 181

8 Oller J A, Prades J, Verbeni M. Phys. Rev. Lett. 2005, **95**: 172502

9 Oller J A. Eur. Phys. J. A, 2006, **28**: 63

10 Oller J A, Prades J, Verbeni M. Eur. Phys. J. A, 2007, **31**: 527

11 Garcia-Recio C, Nieves J, Ruiz Arriola E, Vicente Vacas M J. Phys. Rev. D, 2003, **67**: 076009

12 Roca L, Hyodo T, Jido D. Nucl. Phys. A, 2008, **809**: 65

13 Oset E, Ramos A, Bennhold C. Phys. Lett. B, 2002, **527**: 99; **530**: 260

14 Antonio O. Bouzasa. Eur. Phys. J. A, 2008, **37**: 201

15 Particle Data Group, Yao Y M et al. J. Phys. G, 2006, **33**: 1

16 Manweiler R et al. Phys. Rev. C, 2008, **77**: 015205

17 Prakhov S et al. Phys. Rev. C, 2009, **80**: 025204 [arXiv:0812.1888 [hep-ex]]

18 Abdullah T, Close F E. Phys. Rev. D, 1972, **5**: 2332

19 Close F E, LI Z P. Phys. Rev. D, 1990, **42**: 2194

20 ZHAO Q, Al-Khalili J S, Bennhold C. Phys. Rev. C, 2001, **64**: 052201(R)

21 ZHAO Q, Saghai B, LI Z P. J. Phys. G, 2002, **28**: 1293

22 ZHAO Q, LI Z P, Bennhold C. Phys. Rev. C, 1998, **58**: 2393; Phys. Lett. B, 1998, **436**: 42

23 HE J, Saghai B, LI Z P. Phys. Rev. C, 2008, **78**: 035204

24 LI Z P. Phys. Rev. D, 1993, **48**: 3070; 1994, **50**: 5639; 1995, **52**: 4961; C, 1995, **52**: 1648

25 LI Z P, YE H X, LU M H. Phys. Rev. C, 1997, **56**: 1099

26 ZHAO Q, Al-Khalili J S, LI Z P, Workman R L. Phys. Rev. C, 2002, **65**: 065204

27 ZHONG X H, ZHAO Q, HE J, Saghai B. Phys. Rev. C, 2007, **76**: 065205

28 ZHONG X H, ZHAO Q. Phys. Rev. C, 2009, **79**: 045202; Chinese Physics C, 2009, **33**: 1377

29 ZHONG X H, ZHAO Q. Phys. Rev. D, 2008, **77**: 074008; Phys. Rev. D, 2008, **78**: 014029

30 Isgur N, Karl G. Phys. Lett. B, 1977, **72**: 109; Phys. Rev. D, 1979, **19**: 2653; 1981, **23**: 817; 1979, **20**: 1191

31 Bugg D V, Sarantsev A V, ZOU B S. Nucl. Phys. B, 1996, **471**: 59; LI L, ZOU B S, LI G L. Phys. Rev. D, 2003, **67**: 034025; Lohse D et al. Nucl. Phys. A, 1990, **516**: 513; Bramon A, Grau A, Pancheri G, Phys. Lett. B, 1992, **289**: 97; Bramon A, Escribano R, J. L. Lucio Martinez, Napsuciale M. Phys. Lett. B, 2001, **517**: 345; Roca L, Palomar J E, Oset E, Chiang H Q. Nucl. Phys. A, 2004, **744**: 127; Klingl F, Kaiser N, Weise W. Z. Phys. A, 1996, **356**: 193

32 WU F Q, ZOU B S. Chinese Physics C, 2008, **32**: 629

33 I. Zychor et al. Phys. Rev. Lett., 2006, **96**: 012002

34 Garcia-Recio C, Lutz M F M, Nieves J. Phys. Lett. B, 2004, **582**: 49

35 WU J J, Dulat S, ZOU B S. Phys. Rev. D, 2009, **80**: 017503

36 Mast T S, Alston-Garnjost M, Bangerter R O, Barbaro-Galtieri A S, Solmitz F T and Tripp R D. Phys. Rev. D, 1976, **14**: 13

37 Berley D et al. Phys. Rev. D, 1970, **1**: 1996; 1971, **3**: 2297

38 Jones M, Levi Setti R, Merrill D, Tripp R D. Nucl. Phys. B, 1975, **90**: 349

39 Alston-Garnjost M, Kenney R W, Pollard D L, Ross R R, Tripp R D, Nicholson H, Ferro-Luzzi M. Phys. Rev. D, 1978, **17**: 2216; Phys. Rev. Lett., 1977, **38**: 1003

40 Kim J K. Phys. Rev. Lett., 1965, **14**: 29; Columbia University Report, Nevis, 1966, **149**; Phys. Rev. Lett., 1967, **19**: 1074

41 Evans D, Major J V, Rondio E, Zakrzewski J A, Conboy J E, Miller D J, Tymieniecka T. J. Phys. G, 1983, **9**: 885

42 Ciborowski J et al. J. Phys. G, 1982, **8**: 13

43 Armenteros R et al. Nucl. Phys. B, 1970, **21**: 15

44 Ponte R A et al. Phys. Rev. D, 1975, **12**: 2597

45 Baxter D F et al. Nucl. Phys. B, 1973, **67**: 125

46 Cameron W, Franek B, Gopal G P, Kalmus G E, Bacon T C, Butterworth I, Stern R A. Nucl. Phys. B, 1981, **193**: 21

47 Conforto B et al (Rutherford-London collaboration). Nucl. Phys. B, 1976, **105**: 189

48 Mast T S, Alston-Garnjost M et al. Phys. Rev. D, 1975, **11**: 3078

49 London G W et al. Nucl. Phys. B, 1975, **85**: 289