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BONN–GATCHINA PARTIAL WAVE ANALYSIS: SEARCH FOR HIGH SPIN BARYON STATES*

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The combined analysis of the pion-induced and photoproduction data reveals evidences for unknown nucleon resonances in the fourth resonance region. Two solutions with different pattern of high spin, positive parity states were found. Although the first solution shows a rather large mass gap between high spin baryons with positive and negative parities, the second solution supports the idea of chiral symmetry restoration at high energies. The new polarization data should provide a necessary information to distinguish these two solutions.

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1. Introduction

In spite of the considerable successes of the quark model at low energies [1, 2, 3, 4, 5, 6] it faces a set of serious problems at the mass region above 1900 MeV where it predicts much more nucleon states than have been observed experimentally.

It is possible that our knowledge of the nucleon spectrum is too limited: it is based almost completely on the analysis of the πN scattering data. However, it is also possible that the quark model is too naive to calculate the spectrum of the excited baryons. Then, the baryon spectrum can be understood from some symmetry properties of the quark interaction. One of the most interesting ideas is a possibility for a restoration of the chiral symmetry at high masses [7, 8, 9]. Then the high mass baryons should be produced as parity doublets. Such property is not predicted by existent quark models.

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In this paper, we report properties of nucleon resonances with masses of about 2 GeV from a coupled-channel partial wave analysis of a large number of pion and photo induced reactions. The analysis methods are documented in [10, 11, 12].

2. Data base

The reported coupled-channel partial wave analysis uses the πN elastic amplitudes from SAID [13] and data on the reactions $\pi^- p \to n\eta$, $\pi N \to \Lambda K$, $\pi N \to \Sigma K$, $\gamma p \to p\pi^0$, $\gamma p \to n\pi^+$,$\gamma p \to \Lambda K^+$, $\gamma p \to \Sigma K$, $\pi^- p \to n2\pi^0$, and $\gamma p \to p2\pi^0$, $\gamma p \to p\pi^0\eta$. Measurements of polarization variables, with polarization in the initial or final state or with target polarization, are included in the analysis whenever such data are available. A complete list of the reactions and references to the data is given in Tables 1–5 of Ref. [14].

3. Negative parity nucleon resonances

Our fit of the high statistic data on the $K\Lambda$ photoproduction demands, in addition to the two-pole K-matrix parametrization of the low energy part of the $\frac{1}{2}(\frac{1}{2}^-)$ partial wave, a further resonance at higher mass. A Breit–Wigner amplitude optimized at $M = 1880 \pm 10$, $\Gamma = 88 \pm 12$ MeV which is in striking agreement with the result of the KH84 analysis [15]. This resonance also improves the description of the beam asymmetry and recoil polarization from $\gamma p \to \Sigma^+ K^0$ [16], differential cross-section [17] and polarization observables Ox, Oz and T [18] from $\gamma p \to \Lambda K^+$. The mass scan of the S_{11} state for the solution BG2010-02 is shown in Fig. 1 (a). The fit of our data base with this state included as the third K-matrix pole demonstrated an excellent agreement with the SAID energy independent solution for elastic amplitude in the fitted mass region (up to 2.1 GeV).

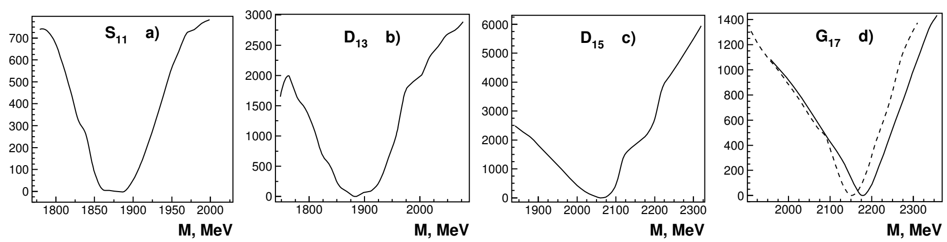

Fig. 1. The change of χ^2 for the mass scan of (a) S_{11}, (b) D_{13}, (c) D_{15} and (d) D_{17}.

Our first analysis of data on photoproduction of π^0, η, and of Λ and Σ hyperons [19, 20] observed the $\frac{1}{2}(\frac{3}{2}^-)$ state with $M = 1875 \pm 25$ MeV and $\Gamma = 80 \pm 20$ MeV. The present analysis uses a significantly richer data base, and the parameters of these state are defined with a much better accuracy. In the present analysis the Breit–Wigner mass was found to be 1875±15 MeV and width 185 ± 20 MeV. The mass scan of this state is shown in Fig. 1 (b).

The RPP [21] lists one high-mass resonance in the $I(J^{\mathrm{P}}) = \frac{1}{2}(\frac{5}{2}^-)$ partial wave, the two-star $N(2200)D_{15}$. It was reported by [15] at $(M, \Gamma) = (2228 \pm 30,\ 310 \pm 50)$ MeV and by [22] at $(2180 \pm 80,\ 400 \pm 100)$ MeV. In our earlier analysis of the η photoproduction data [23] we reported the observation of a D_{15} resonance with a mass of about 2060 MeV. In the present solution, we find, in addition, a significant contribution from this state to $\gamma p \to \Lambda K^+$. The mass scan of the Breit–Wigner state which optimized at $M = 2075 \pm 12$ MeV and $\Gamma = 365 \pm 20$ MeV is shown in Fig. 1 (c). The fit with the $N_{5/2-}(2060)$ state included as the second K-matrix pole reproduces perfectly the πN elastic amplitudes extracted by the SAID up to 2.5 GeV. If the second pole is excluded from the fit, the high energy region cannot be fitted well even after including energy dependent non-resonant terms.

An introduction of a $\frac{1}{2}(\frac{7}{2})^-$ state in the mass region 2100 MeV significantly improves the description of the $\gamma N \to K\Lambda$ differential cross-section and recoil asymmetry [17]. The mass of the state was found to be 2185 ± 20 MeV which is compatible with the RPP numbers [21], the width was optimized at 290 ± 40 MeV. The mass scan is given in Fig. 1 (d).

3.1. Positive parity nucleon resonances

Above the Roper resonance, we observe a pole at $(1690^{+25}_{-10}, 210 \pm 25)$ MeV or $(1695 \pm 15, 220 \pm 30)$ MeV for BG2010-01 and BG2010-02 (Re,-2Im), respectively, which we identify with the known 3-star $N(1710)P_{11}$. A second resonance is seen at $(1860 \pm 20, 110^{+30}_{-10})$ MeV or $(1850^{+20}_{-50}, 360 \pm 40)$ MeV, respectively, with a width which depends sensitively on the solution. We call this resonance $N_{1/2^+}$ (1870).

In the $\frac{1}{2}(\frac{3}{2}^+)$ partial wave we observe above the well known $N(1720)P_{13}$ at least one additional state: $N(1900)P_{13}$ [24]. However, a better fit is obtained when a two-pole structure is assumed. Future experiments will have to decide if the splitting into two resonances is real. However, the existence of at least one pole is mandatory to achieve an acceptable fit.

The lowest $I(J^{\mathrm{P}}) = \frac{1}{2}(\frac{5}{2}^+)$ state, $N(1680)F_{15}$, is well established and its properties are known with a good precision. At higher masses a rather narrow state, with the mass 1882 ± 10 and width 95 ± 20, was observed in the KH84 analysis of the elastic πN data [15] and confirmed by SAID [13], although with a notably lower mass (1818 MeV). In contrary, an observation of a rather broad state ($M = 1903 \pm 87$, $\Gamma = 490 \pm 310$ MeV) was reported from the combined analysis of the πN elastic data and $\pi N \to 2\pi N$ data [25].

Our fit of photoproduction data demands a second $5/2^+$ state at a considerably higher mass. In a two-pole five-channel K-matrix parameterization of the F_{15} partial wave, the position of the second pole was found to be at $2075 \pm 15 - i290 \pm 10$ in solution BG2010-01, and at $2045 \pm 20 - i260 \pm 15$ MeV in BG2010-02. The elastic πN amplitude is described with a modest $\chi^2/N_{\rm data} = 4.44(4.72)$ per data point for BG2010-01(02), see Fig. 2 (a).

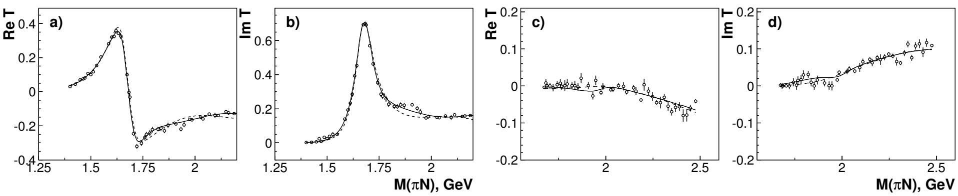

Fig. 2. (a) Real and (b) imaginary part of the $\frac{1}{2}(\frac{5}{2})^+$ partial wave amplitude and fit BG2010-2 with three poles (solid curves) and two poles (dashed curves). (c) Real and (d) imaginary part of the $\frac{1}{2}(\frac{7}{2})^+$ partial wave and fit BG2010-1 (solid curves) and BG2010-02 (dashed curves).

The structure in the F_{15} elastic amplitude at about 1.9 GeV (Fig. 2 (a,b)) is not well described in the fit with two K-matrix poles. Hence we introduced a three-pole five-channel K-matrix to describe the F_{15} partial wave. The new solutions reproduce the SAID F_{15} amplitude with $\chi^2/N_{\rm data} = 1.88(1.77)$ starting from BG2010-01(02). However, the pole position of this pole is not well defined: it can be located anywhere in the mass region 1800–1950 MeV; its imaginary part corresponds to a width of 120–300 MeV. In the three pole K-matrix solution the pole situated above 2 GeV is shifted to higher masses at about 40 MeV.

Observations of a $\frac{1}{2}(\frac{7}{2})^+$ state in the 2 GeV mass region were reported from set of analysis. Its Breit–Wigner mass and width were determined to $M = 2005 \pm 150$ MeV, $\Gamma = 350 \pm 100$ in [15], to $M = 1970 \pm 50$ MeV, $\Gamma = 350 \pm 120$ in [22], and to $M = 2086 \pm 28$ MeV, $\Gamma = 535 \pm 120$ in [25]. However, this state was not seen in the analysis [13] (or at least was not reported). Indeed, the $\frac{1}{2}(\frac{7}{2})^+$ amplitude (see Fig. 2 (c), (d)) shows no significant structure. At present we found two very different mass positions. In the solution BG2010-01, the mass optimized for 1980 ± 25 MeV and width for 190 ± 35 MeV. In the solution BG2010-2, mass and width were found to be 2070 ± 30 MeV and 250 ± 35 MeV. These two solutions have very different helicity couplings for the F_{17} state; therefore more precise polarization experiments should distinguish between them.

4. Interpretation

AdS/QCD is an analytically solvable "gravitational" theory simulating QCD which is defined in a five-dimensional Anti-de Sitter (AdS) space embedded in six dimensions [26, 27]. In a special variant of AdS/QCD, a two-parameter mass formula was derived [28] which reproduces the baryon mass spectrum from the solution BG2010-01 with a surprising precision. We mention that the mass formula had been suggested before on an empirical basis [29].

The states observed in the BG2010-02 solution are collected in Table I.

TABLE I

Nucleon resonances as parity doublets.

$N_{1/2^+}(1710)$	$N_{1/2^-}(1650)$	$N_{3/2^+}(1720)$	$N_{3/2^-}(1700)$
$N_{5/2^+}(1680)$	$N_{5/2^-}(1675)$	$N_{1/2^+}(1880)$	$N_{1/2^-}(1895)$
$N_{3/2^+}(1900)$	$N_{3/2^-}(1875)$	$N_{5/2^+}(2095)$	$N_{5/2^-}(2075)$
$N_{7/2^+}(2100)$	$N_{7/2^-}(2190)$	$N_{9/2^+}(2220)$	$N_{9/2^-}(2250)$

The occurrence of parity doublets in the mass spectrum of mesons and baryons is surprising. The harmonic oscillator states with positive and negative parity alternate, and in quark models, even in fully relativistic quark models, this pattern survives. In meson spectroscopy many resonances also have parity partners with exception of those situated on the leading Regge trajectory. In [30] it is argued that formation of the spin-parity partners of mesons on the leading Regge trajectory could be suppressed by angular momentum barrier factors. In photoproduction of baryon resonances such a suppression is not expected. Photoproduction experiments could thus be of decisive importance to clarify the dynamics of highly excited hadrons. Unfortunately, the two solutions for the mass of the $5/2^+$ and $7/2^+$ resonances prevent that a final decision can be made at present. Future experiments with polarized beam and target which will help to distinguish between two solutions are urgently required.

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