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Dibaryon Signals in NN Scattering Data and Further Measurement at COSY, LEPS and CSR*

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Abstract: The NΔ and $\Delta\Delta$ dibaryon resonances are studied by calculating the NN scattering phase shifts with explicitly coupling these dibaryon channels in a multi-channel coupling calculation with two quark models. These quark models, the chiral quark model and quark delocalization color screening model, describe the NN *S*-, *D*-wave phase shifts below the π production threshold quantitatively well. Both quark models predict the $^1D_2$ resonance discovered in NN partial wave phase shift analysis and the $J=1$ or 3 isoscalar resonance recently reported by CELSIUS-WASA Collaboration are N$\Delta\,^5S_2$ and $\Delta\Delta\,^7S_3$ resonance, respectively. Further measurements at COSY, LEPS and Lanzhou Cooling Storage Ring(CSR) to check the $\Delta\Delta$ resonance are discussed.

Key words: nucleon-nucleon scattering; dibaryon; quark model

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1 Introduction

Almost all quark models predict there should be quark-gluon exotics, $q\bar{q}q\bar{q}$, $q^3q\bar{q}$, q^6, glueball and quark-gluon hybrid, etc. Lattice QCD calculations support quark model predictions. Quark benzene[1] strangelet and so on have been proposed. However up to now there is no experimentally well established exotics. The NN scattering phase shift analysis had found few resonances[2] and different explanations, including dibaryon resonance, were proposed[3]. Recently CELSIUS-WASA Collaboration reported preliminary results on the ABC anomaly in the production cross section of the pn$\to$d$\pi^0\pi^0$ reaction that suggests the presence of an isoscalar $J^p=1^+$ or 3^+ subthreshold $\Delta\Delta$ resonance with an estimated mass at ~2 410 MeV and width of <100 MeV[4].

There is no reliable theory to deal with the NN scattering in the resonance energy region. The present lattice QCD technique is in principle not able to deal with resonance because hadron resonance is not an eigen state of a Hamiltonian but a collective state, i. e., a superposition of infinite scattering state. Only if the resonance is narrow and can be approximated as a bound state then one can use lattice QCD technique to calculate its energy. If the energy shift due to coupling of this bound state to the scattering states is large then

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the lattice QCD result will be not reliable. The chiral perturbation is hard to be extended to resonance energy region to be as reliable as in the low energy region. Quark model can be employed to do detailed quantitative calculation of the NN scattering in the resonance energy region but of course a model one. We use two quark models, the chiral quark model (ChQM)[3] and the quark delocalization color screening model (QDCSM)[5] to do NN scattering calculation with the NΔ and ΔΔ dibaryon channels explicitly coupled to study if these couplings give rise to resonance and if the experimentally observed resonance can be explained by these channel coupling resonances. These two models have been shown to describe the S- and D-wave NN scattering below π production threshold quantitatively well[6]. In these channel coupling calculations the Δ is assumed to be a stable particle and so if there is resonance appeared it is a Feshbach channel coupling resonance and the calculated width only includes the open channel coupling effect while the width of Δ itself has not been taken into account yet. We take a simple approximation to include the width of a bound Δ to the NΔ and ΔΔ dibaryon resonance widths.

2 Quark Models and Cluster Model Wave Functions

Chiral quark model (ChQM) is wide used in baryon-baryon scattering. There are different versions in the market. Here we use the Salamanca version which has been used to study the hadron spectroscopy and hadron scattering together[3]. In this model there are effective one gluon exchange and (pseudo scalar and scalar) meson exchange q-q interactions in addition to the color confinement. Do these meson exchange describe the short range quark interaction well is an open question.

Another quark model used is the quark delocalization color screening model (QDCSM)[5] which is proposed in order to understand the similarity between the molecular force and nuclear force. Hydrogen atom is electric neutral and the hydrogen bound is due to electron delocalization between two interacting hydrogen atoms. Nucleon is color neutral, QDCSM successfully reproduce the NN short range repulsion and intermediate range attraction by quark delocalization between two interacting nucleons and so provide a natural explanation why the nuclear force and molecular force are similar. In QDCSM there is only effective one gluon and the Goldstone boson π exchange q-q interaction but no σ meson exchange. The confinement interaction is reparameterized by introducing the color screening for quark pair occupying single quark orbits with different centers. QDCSM and ChQM have different mechanism for NN intermediate range attraction but they give almost the same NN S and D wave phase shifts below π production threshold. Therefore it is interesting to compare their predicted NN interaction in the resonance energy region and the dibaryon resonances properties.

In both quark models the color-flavor-spin wave function of hadrons are the group chain

$$SU_{18}^{cf\sigma} \supset SU_3^c \times SU_6^{f\sigma} \supset SU_f^3 \times SU_2^\sigma$$

classified wave function. The orbital wave function is the product of single quark orbital wave function which is assumed to be left and right centered Gaussian functions in ChQM

$$\phi_R(\boldsymbol{r}) = \left(\frac{1}{\pi b^2}\right)^{3/4} \exp\left(-\frac{\boldsymbol{r}-(\boldsymbol{S}/2)^2}{2b^2}\right) ,$$

$$\phi_L(\boldsymbol{r}) = \left(\frac{1}{\pi b^2}\right)^{3/4} \exp\left(-\frac{\boldsymbol{r}-(\boldsymbol{S}/2)^2}{2b^2}\right) , \quad (1)$$

where b is a parameter describing the size of baryon and is determined by baryon spectroscopy. For QDCSM the delocalized left and right single quark wave function is used,

$$\psi_l(\boldsymbol{r}) = (\phi_L + \varepsilon\phi_R)/N(\varepsilon) ,$$

$$\psi_r(\boldsymbol{r}) = (\phi_R + \varepsilon\phi_L)/N(\varepsilon) ,$$

$$N(\varepsilon) = \sqrt{1+\varepsilon^2+2\varepsilon\langle\phi_R \mid \phi_L\rangle} , \quad (2)$$

where $\phi_L(\boldsymbol{r})$, $\phi_R(\boldsymbol{r})$ are the left, right centered

Gaussian function of Eq. (1), $N(\varepsilon)$ is the normalization factor. ε is the delocalization parameter which is determined dynamically by the minimization of the diagonal matrix element of the six quark system Hamiltonian with the following two baryon channel wave functions.

The NN, NΔ, and $\Delta\Delta$ two baryon channel wave functions are:

$$\Psi_{NN} = \mathscr{A}[\psi_{N_1}(q_1q_2q_3)\psi_{N_2}(q_4q_5q_6)]^{[c]IJ}_{WM_IM_J},$$
$$\Psi_{N\Delta} = \mathscr{A}[\psi_N(q_1q_2q_3)\ \psi_\Delta(q_4q_5q_6)]^{[c]IJ}_{WM_IM_J},$$
$$\Psi_{\Delta\Delta} = \mathscr{A}[\psi_\Delta(q_1q_2q_3)\psi_\Delta(q_4q_5q_6)]^{[c]IJ}_{WM_IM_J}, \quad (3)$$

where $\mathscr{A}$ is the six quark antisymmetrization operator, ψ_N, ψ_Δ are the N, Δ baryon wave functions, $[\ ]^{[c]IJ}_{WM_IM_J}$ means coupling the two baryons into total color symmetry $[c]W$, isospin IM_I, spin JM_J. The separation $\boldsymbol{S}$ is implicitly included through the single quark orbital wave function Eqs. (1), (2) and play the generating coordinate here. The Resonating Group Model (RGM) wave-function can be obtained from the Generating Coordinate Model (GCM) wave-function Eq. (3) through factorizing the total Center of Mass (CM) motion wave function. In QDCSM case, a projection to eliminate the spurious CM motion is needed but the effect is found to be minor[7].

The model parameters and the properties of deuteron in two models are listed in Table 1. The model parameters can be varied within a range, the baryon size parameter b can be varied from 0.48 to 0.64 fm and the other parameters varied correspondingly, the S and D wave phase shifts below π production threshold still can be fitted quantitative well. The more details can be found in Refs. [3, 5, 6].

Table 1 Parameters of ChQM and QDCSM and the properties of deuteron in two models

	$m_{u,d}$/MeV	α_{ch}	α_s
ChQM &	313	0.027	0.485
QDCSM	m_π/MeV	Λ/fm^{-1}	b /fm
	138	4.2	0.518
	a_c/(MeV/fm^2)	m_σ/MeV	μ /fm^{-2}
ChQM	46.938	675	——
QDCSM	56.75	——	0.45
	B_d/MeV	$\sqrt{r_d^2}$ /fm	P_d(%)
ChQM	2.0	1.96	4.86
QDCSM	1.94	1.93	5.25

3 Results and Discussions

Figs. 1 and 2 display the calculated $^1S_0$ and $^3S_1$ phase shifts up to the resonance energy region. Multi-channel coupling effects are included. The partial wave phase shift analysis (PWA) results SP07[8] are displayed too. These results show that both quark models describe the S-wave phase shifts quantitatively well below the π production threshold. However both quark models give too much attraction in the higher scattering energy region and show that they are both lack of short range repulsion.

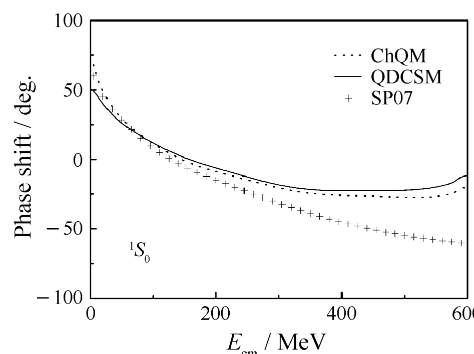

Fig. 1 The $^1S_0$ phase shifts calculated by ChQM and QDCSM. The SP07 PWA data points are also displayed.

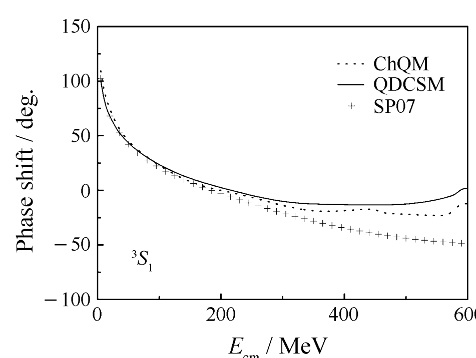

Fig. 2 The same as Fig. 1 for $^3S_1$.

Figs. 3—6 display the D-wave results. Both quark models calculated phase shifts fit quantitatively well with the PWA results up to resonance energy region. In the single channel approximation, both quark models give bound $^7S_3$ di-Δ bound state. After coupling to NN$^3D_3$ scattering, ChQM and QDCSM give rise to channel coupling resonance at 2.393 and 2.357 GeV respectively and the same NN width $\Gamma_{NN}=14$ MeV before including the Δ width and $\Gamma_{inel}=136$ and 96 MeV respectively after including the bound Δ width[9]. These are close to the reported value by CELSIUS-WASA Collaboration[4]. In the $^1D_2$ partial wave case, QDCSM predicted a bound and ChQM gave an almost bound $^5S_2$ NΔ state. After coupling to NN$^1D_2$ scattering, QDCSM gives rise to a channel coupling resonance at $M_R=2.168$ MeV and a width $\Gamma_{NN}=4$ MeV before including the Δ width and $\Gamma_{inel}=117$ MeV after including the bound Δ width[9], which are close to the PWA result[2].

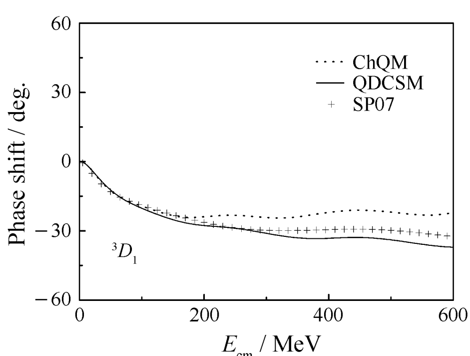

Fig. 3　The same as Fig. 1 for $^3D_1$.

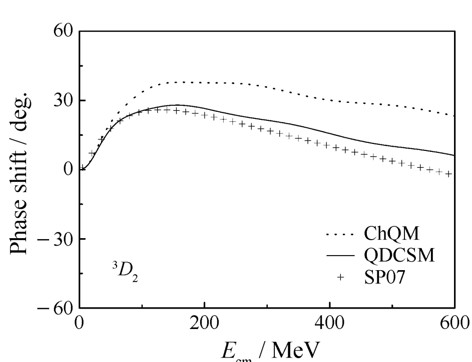

Fig. 4　The same as Fig. 1 for $^3D_2$.

PWA found other partial wave resonances $^3P_2$—$^3F_2$ and $^3F_3$. Two quark models have not obtained these resonances in their present version.

From these results we suggest that the observed $^1D_2$ resonance in PWA is a N$\Delta$$^5S_2$ dibaryon resonance. The CELSIUS-WASA Collaboration reported $J=1$ or 3 isoscalar resonance is quite possible a di-$\Delta$$^7S_3$ resonance.

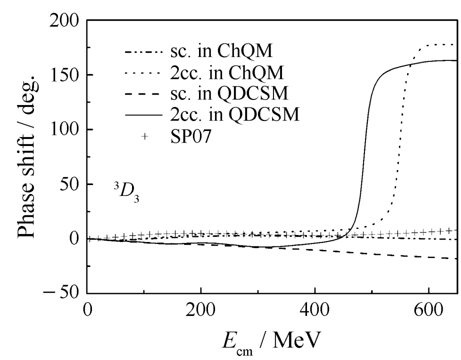

Fig. 5　The same as Fig. 1 for $^1D_3$.

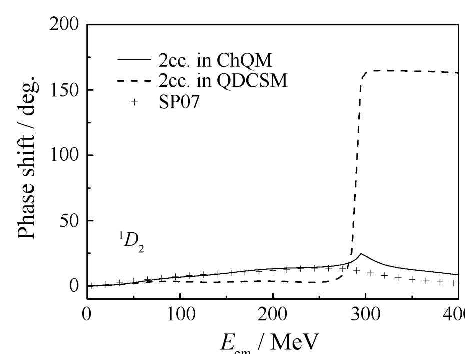

Fig. 6　The same as Fig. 1 for $^1D_2$.

4　New Measurement at COSY, LEPS and CSR

CELSIUS-WASA collaboration reported results are preliminary. They will continue their measurement at COSY. CSR is a facility quite similar to COSY. We suggest to plan the following measurements.

(a) To repeat the pp, pd and dp elastic NN scattering measurement especially in the resonance energy region to check the precision of the CSR facilities and data analysis systems. To improve the NN scattering data basis if possible.

(b) To do the $pp \to pp\pi^0$, $pn\pi^+$, $pd \to pd\pi^0$, $pd\pi^0\pi^0$, $pd\pi^+\pi^-$, $dp \to dp\pi^0$, $dp\pi^0\pi^0$, $dp\pi^+\pi^-$ exclusive measurements to check the CELSIUS-WASA results and search for dibaryon resonance signals.

(c) LEPS is a good place to do γd reaction measurement. The $\gamma d \to d\pi$, $d\pi\pi$, $NN\pi$, $NN\pi\pi$ will provide $N\Delta$, di-Δ or d^* dibaryon resonance information. It is a good check of the present PWA and SELSIUS-WASA results on the dibaryon signals. The energy should cover these resonance energies.

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