corresponding energies may supply useful information.

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Possible Existence of a Deeply Bound Δ-Δ System

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Being motivated by the observation of an anomaly in the polarization of protons in $\gamma d \to pn$, we have investigated the possible existence of deeply bound dibaryon states. The nonrelativistic one-boson-exchange potential model (π, η, ρ, and ω exchanges) for two Δ isobars gives binding energies around 100 MeV for $I=0$, $J=3$ and $I=3$, $J=0$. Existence of this $I=0$ dibaryon resonance reproduces experimentally observed cross sections in the $I=0$, $NN\to d\pi\pi$ and $NN\to NN\pi\pi$ channels.

A recent experimental study[1] on the proton polarization in deuteron photodisintegration reports a resonancelike behavior at around 550 MeV in photon energy. The observed polarization increases sharply with photon energy, reaching a maximum of $(-80\pm7)\%$. Theoretical analyses by Ogawa *et al.*,[2] by George,[3] and by Hasselmann[4] have failed to reproduce such structure in the polarization. As has been noted,[1] this structure is hard to understand from a composite intermediate state, but is easily understood if there is an appreciable amount of dibaryon resonant amplitudes. That is, a resonance in the two-nucleon system with a mass of approximately 2380 MeV will give an imaginary amplitude of the Breit-Wigner type, as is shown in Fig. 1, which will interfere with almost real amplitudes (Born + NN^*) and will give a structure similar to what has been observed (see Ref. 2 for further details). We looked for nucleon-isobar combinations, which may be deeply bound to give the total mass in this energy range, and discuss here our calculations showing the possible existence of a deeply bound Δ-Δ system. We also discuss what effects this dibaryon resonance might have on other channels, such as $NN\to d\pi\pi$ and $NN\to NN\pi\pi$.

The calculation presented here is based on the nonrelativistic one-boson-exchange (OBE) potential model, where the pion, η meson, ρ meson, and ω meson are the exchanged bosons. For simplicity we consider only the S state. The coupling constants are varied around experimentally known values or values predicted by the quark model. A hard-core barrier is assumed at around the range of the lightest mesons not included in the present analysis. Then the Schrödinger equation is solved, and the binding energy is determined for each combination of the coupling constants and the hard-core radius.

π- and η-exchange potential.—For the $\Delta\Delta\pi$ vertex function, we take formula,[5]

$$\langle s'|\Gamma_\alpha(p',p)|s\rangle = -3(f_\pi/m_\pi)\bar{u}^\mu(p',s')(\tau)_\alpha\gamma_5 u_\mu(p,s), \tag{1}$$

where τ is the isospin operator ($I=\frac{3}{2}$), and $u^\mu(p,s)$ is a Rarita-Schwinger spinor ($s=\frac{3}{2}$). In the nonrelativistic limit Eq. (1) reduces to a Yukawa-type potential. For π and η exchange in the S state, the potential takes the following form:

$$V^{(\pi+\eta)}(r) = \frac{1}{3}\frac{f_{\Delta\Delta\pi}^2}{4\pi}[\vec{\tau}(1)\cdot\vec{\tau}(2)][\vec{\sigma}(1)\cdot\vec{\sigma}(2)]\frac{\exp(-m_\pi r)}{r} + \frac{1}{3}\frac{f_{\Delta\Delta\eta}^2}{4\pi}[\vec{\sigma}(1)\cdot\vec{\sigma}(2)]\frac{\exp(-m_\eta r)}{r}. \tag{2}$$

ρ- and ω-exchange potentials.—We adopt the $\Delta\Delta\rho$ (or $\Delta\Delta\omega$) coupling used by Arenhövel[5] in the nonrelativistic limit. Then the potential for ρ and ω exchange in the S state is

$$V^{(\rho+\omega)}(r) = [\vec{\tau}(1)\cdot\vec{\tau}(2)]\left\{\frac{g_{\Delta\Delta\rho}^2}{4\pi} + \frac{f_{\Delta\Delta\rho}^2}{4\pi}\frac{2}{3}[\vec{\sigma}(1)\cdot\vec{\sigma}(2)]\right\}\frac{\exp(-m_\rho r)}{r} + \left\{\frac{g_{\Delta\Delta\omega}^2}{4\pi} + \frac{f_{\Delta\Delta\omega}^2}{4\pi}\frac{2}{3}[\vec{\sigma}(1)\cdot\vec{\sigma}(2)]\right\}\frac{\exp(-m_\omega r)}{r}. \tag{3}$$

Coupling constants.—Various choices of coupling constants are tried for the $\Delta\Delta$-boson couplings, since they are not always well-measured experimentally. We use experimental values whenever they are available and make best guesses when they are not. We fix the $\Delta\Delta\pi$ coupling constants from the experimentally determined value for $f_{\Delta N\pi}$ and the static quark model.[5] The $\Delta\Delta\eta$ coupling constant is related to $f_{\Delta\Delta\pi}$ by the quark model:

$$\frac{f_{\Delta\Delta\pi}^2}{4\pi} = 0.005, \quad \frac{f_{\Delta\Delta\eta}^2}{4\pi} = 3\frac{f_{\Delta\Delta\pi}^2}{4\pi}\left(\frac{m_\eta}{m_\pi}\right)^2.$$

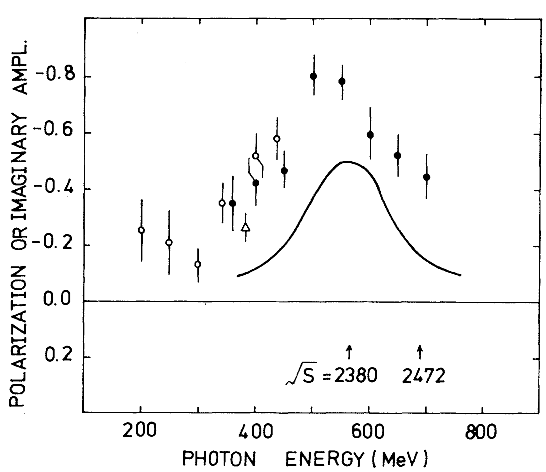

FIG. 1. Proton polarization in $\gamma d \to pn$. Filled circles are data from Ref. 1, open circles are data from Ref. 5 of Ref. 1, and triangle is datum from Ref. 6 of Ref. 1. The curve shows the Breit-Wigner–type imaginary and amplitude due to the $\Delta\Delta$ bound state at $\sqrt{s}=2380$. Note that the unbound $\Delta\Delta$ phase space opens at $\sqrt{s}=2472$.

In fixing the coupling constants for vector mesons, we consider the prediction from SU(3) about the $\Delta\Delta\rho$ to $\Delta\Delta\omega$ coupling ratio to be reliable. We do this since the decuplet-decuplet-octet coupling is unique in the SU(3) scheme and leaves no ambiguity as in the case of the octet-octet-octet coupling. (Note also that the prediction is based only on the isospin properties of ρ, ω, and Δ.) This ratio is

$$\frac{g_{\Delta\Delta\omega}^2}{4\pi} + \frac{f_{\Delta\Delta\omega}^2}{4\pi}\frac{2}{3}(\vec{\sigma}\cdot\vec{\sigma}) = 9\left[\frac{g_{\Delta\Delta\rho}^2}{4\pi} + \frac{f_{\Delta\Delta\rho}^2}{4\pi}\frac{2}{3}(\vec{\sigma}\cdot\vec{\sigma})\right]. \tag{4}$$

We use the quark model to decompose this relation into the following relations:

$$g_{\Delta\Delta\omega}^2/4\pi = 9g_{\Delta\Delta\rho}^2/4\pi, \quad f_{\Delta\Delta\omega}^2/4\pi = 9f_{\Delta\Delta\rho}^2/4\pi, \tag{5}$$

$$f_{\Delta\Delta\rho} = 3.8(m_\rho/6M_\Delta)g_{\Delta\Delta\rho}. \tag{6}$$

The quark model also predicts the equality of $g_{\Delta\Delta\rho}$ and $g_{NN\rho}$. We consider, however, this relation to be less reliable than Eqs. (4) and (5), and will try two different values in the computation of the binding energy. Besides these forces, we

TABLE I. Binding energies for the ΔΔ ($I=0$, $J=3$) and ($I=3$, $J=0$) states. Deeply bound states (binding energy > 10 MeV) cease to exist for hard-core radii larger than 0.38–0.40 fm.

	$\frac{f_{\Delta\Delta\pi}^2}{4\pi}$	$\frac{f_{\Delta\Delta\eta}^2}{4\pi}$	$\frac{g_{\Delta\Delta\rho}^2}{4\pi}$	$\frac{f_{\Delta\Delta\rho}^2}{4\pi}$	$\frac{g_{\Delta\Delta\omega}^2}{4\pi}$	$\frac{f_{\Delta\Delta\omega}^2}{4\pi}$	Hard core radius (fm)	Binding energy $I=0$, $J=3$ (MeV)	Binding energy $I=3$, $J=0$ (MeV)
A	0.005	0.23	0.52	0.096	4.7	0.86	0.2	82	280
B	0.005	0.23	0.89	0.138	8.0	1.24	0.2	340	351
C	0.005	0.23	0.52	0.096	4.7	0.86	0.25	22	108
D	0.005	0.23	0.89	0.138	8.0	1.24	0.25	133	140
E	0.005	0.23	0.52	0.096	4.7	0.86	0.3	11	65
F	0.005	0.23	0.89	0.138	8.0	1.24	0.3	80	86

take a hard-core potential to simulate effects of higher boson exchanges. The hard-core potential for the *NN* system is generally understood to come from the vector-meson exchange. Since we have included the vector mesons in the analysis, an additional hard-core potential, if necessary, will be due to higher-mass mesons such as f and A_2. Here, we guess this radius to be 0.25–0.3 fm by scaling the fitted value,[6] 0.4–0.53 fm, for the *NN* system inversely proportional to the mass of the responsible meson. Allowing for possible uncertainties in our experimental knowledge about $g_{\Delta\Delta\rho}$ and the hard-core radius, we choose six different combinations of the coupling constants and the hard-core radius, given by $A-F$ in Table I.

Results of computations.—Schrödinger equations for the Δ-Δ system under the influence of the π, η, ρ, and ω exchange potentials, Eqs. (2) and (3), have been solved for all allowed spin-isospin combinations. From the expectation values for the $\vec{\tau}(1)\cdot\vec{\tau}(2)$ and $\vec{\sigma}(1)\cdot\vec{\sigma}(2)$ terms (see Table II), one can make guesses that deeply bound states, if they exist, would have $I=0$, $J=3$ or $I=3$, $J=0$. In fact, the π and ρ exchange potentials are potentially an order of magnitude more attractive for the Δ-Δ system than for the *N-N* system due to the isospin-spin dependence of these potentials in the low-energy region. Numerical computations[7] verify this conjecture (see Table I) and give bound states for $I=0$, $J=3$ and $I=3$, $J=0$. The binding energies thus calculated are an order of magnitude larger than those for the *NN* system. The exact values, however, depend critically upon the hard-core radius, and to a lesser extent, upon the $\rho\Delta\Delta$ coupling. We consider that a hard-core radius of 0.2 fm represents a case where f and A_2 do not give highly repulsive potentials and 0.3 fm represents a case where f or A_2 gives a repulsive potential as high as ω or ρ in the *NN* system. We conclude that the $I=0$, $J=3$ state has a good chance to be deeply bound by about 100 MeV and produces the observed anomaly at around $\sqrt{s}=2380$ MeV in $\gamma d \to pn$. The other dibaryon resonance may also exist around $\sqrt{s}=2380$ MeV as the OBE potential model indicates.[8]

Possible relation with the ABC effect.—A series of experiments by the Saclay deuteron group[9] and by the Heidelberg–Tel-Aviv group[10] studied the so-called *ABC* effect[11] in $n+p\to d+M^0$, where M is missing mass and $I(M^0)=0, 1$. They ob-

TABLE II. Expectation values of $(\vec{\tau}\cdot\vec{\tau})\cdot(\vec{\sigma}\cdot\vec{\sigma})$ for various total spin-isospin combinations.

Total isospin	Total spin	$\langle\vec{\tau}(1)\cdot\vec{\tau}(2)\rangle$	$\langle\vec{\sigma}(1)\cdot\vec{\sigma}(2)\rangle$	$\langle\vec{\tau}\cdot\vec{\tau}\rangle\langle\sigma\cdot\sigma\rangle$
0	1	−15	−11	+165
0	3	−15	9	−135
1	0	−11	−15	+165
1	2	−11	−3	+33
2	1	−3	−11	+33
2	3	−3	9	−27
3	0	9	−15	−135
3	2	9	−3	−27

served a strong enhancement in the $I=0$ two-pion channel at a missing mass of ~300 to 350 MeV. One interesting feature of this effect is that the production cross section is highly dependent on the total c.m. energy, $\sqrt{s}$. In the *np* collision,[10] the effect takes place at around $\sqrt{s} \sim 2450$ MeV with a full width at half-maximum (FWHM) of about 240 MeV. Because of this dependence on the c.m. energy, it is generally understood that the *ABC* effect is not a manifestation of a boson resonance but rather of final-state interactions.[12] In the light of our model, it may be just a decay mode of the deeply bound $I=0$ $\Delta\Delta$ system. In fact, the width and the position of the observed cross section are in good agreement with a Breit-Wigner-type dibaryon resonance at $\sqrt{s}=2380$ with FWHM of 160 MeV multiplied by the $d\pi\pi$ phase space[13] (see Fig. 2).

Possible relation with the $NN\rightarrow NN\pi\pi$ ($I=0$) reaction.—Double-pion production in the *NN* collision at low energies has not been very well studied. However, the $I=0$ and $I=1$ total cross sections in the c.m. energy range ~2300 to 2700 MeV show a clear difference in magnitude, as well as in the energy dependence.[14] The difference between $\sigma(pn\rightarrow pn\pi^+\pi^-)$ and $\sigma(pp\rightarrow pp\pi^+\pi^-)$ measured experimentally has been plotted in Fig. 2. The $pn\rightarrow pn\pi^+\pi^-$ cross section is known to be dominated by the $I=0$ amplitude in this energy range.[14] This excess of the $I=0$ contribution is easily explained by our model as another decay mode of the deeply bound $\Delta\Delta$ system. In fact the shape of the $I=0$ cross section is in perfect agreement with a Breit-Wigner-type dibaryon resonance at $\sqrt{s}=2380$ with FWHM of 160 MeV multiplied by the $NN\pi\pi$ phase space[13] (see Fig. 2).

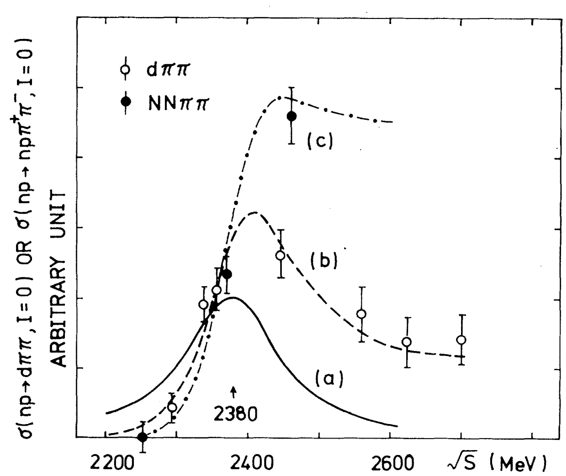

FIG. 2. $\sigma(np\rightarrow d\pi\pi, I=0)$ and $\sigma(np\rightarrow np\pi^+\pi^-, I=0)$ vs total c.m. energy of the two nucleons. Curve *a* is the Breit-Wigner curve for the $\Delta\Delta$ bound state; curve *b* is the expected reflection of the dibaryon resonance to the $d\pi^+\pi^-$ ($I=0$) final state; curve *c* is that to the $np\pi^+\pi^-$ ($I=0$) final state. Experimental points for curves *b* and *c* are taken from Fig. 2(d) of Ref. 10 and from Fig. 9 of Ref. 12, respectively.

The $\Delta\Delta$ system is shown theoretically to have a good chance to form deeply bound states with $I=0$, $J=3$ and $I=3$, $J=0$. The critical point in the computation of the binding energies is the coupling strength of the $\Delta\Delta\rho$ and the hard-core radius. The anomaly observed in $\gamma d\rightarrow pn$ is interpreted to be due to this ($I=0$, $J=3$) dibaryon resonance. Then the excess of the $I=0$ amplitudes in the dibaryon cross sections, $NN\rightarrow d\pi\pi$ and $NN\rightarrow NN\pi\pi$, is most naturally explained. If this interpretation is right, the two Δ isobars are proven to be bound by about 100 MeV, deeper than the half-width of the isobar, forming a genuine dibaryon resonance. This fact, together with experimental studies on the $I=3$, $J=0$ resonance, in future will have a very important bearing in understanding the quark dynamics, in particular, in the six-quark system.

Based on these interpretations, one can estimate the decay branching ratio of this $I=0$ dibaryon resonance. In doing so, we assume for simplicity that the resonance occurs in the $L=3$ partial wave for the *NN* system and that the branching ratio is appreciable only for the $NN\pi\pi$, $d\pi\pi$, and *NN* channels. The partial widths calculated depend on the ratio $\Gamma_{NN\pi\pi}/\Gamma_{d\pi\pi}$, and they are (in MeV) for $\Gamma_{NN\pi\pi}/\Gamma_{d\pi\pi}=5$, $\Gamma_{NN\pi\pi}=118$, $\Gamma_{d\pi\pi}=23.6$, and $\Gamma_{NN}=18$, and for $\Gamma_{NN\pi\pi}/\Gamma_{d\pi\pi}=3$, $\Gamma_{NN\pi\pi}=111$, $\Gamma_{d\pi\pi}=37$, and $\Gamma_{NN}=12$.

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