Mass spectrum of the strange dibaryon

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Based on the diquark-cluster model, the mass spectrum of low-lying $S=-1$ strange dibaryons is predicted. In this scheme, two $J^P=0^-$ states with $I=\frac{1}{2}$ and $\frac{3}{2}$ are degenerate at the lowest-energy level, around 2.2 GeV c.m. energy. These states can be assigned to the strange-dibaryon candidate at 2.14 GeV observed by Piekarz in the missing-mass spectrum for the $d(K^-,\pi^-)X$ reactions. A similar experiment using polarized deuterons is proposed for the purpose of testing the validity of this assignment.

I. INTRODUCTION

In a previous paper[1] we showed that the predictions of the diquark-cluster model[2] for the mass spectrum and the partial decay widths of nonstrange dibaryons agree well with the experimental evidence[3–7] both for broad and narrow resonances. It should be emphasized that the group of narrow resonances observed by the Rice-LAMPF group,[3] the ETH group,[4] Siemiarczuk, Stepaniak, and Zielinski,[5] and Tatisheff *et al.*[6] are all well explained by the diquark-cluster model. Concerning recent developments, we point out that the Bonn group[8] observed a narrow resonance with $\Gamma\sim 4$ MeV at 2.017 GeV c.m. energy in the γd reaction and this can be assigned to the lowest $J^P=0^+$ state C_2 in the diquark-cluster model, of which the mass and width are predicted to be 2.02 GeV and ~ 3 MeV, respectively. The diquark-cluster model also predicts the existence of several $I=0$ narrow nonstrange dibaryons with $J^P=1^+$, 1^-, and 3^- (Ref. 9). Experimentally, polarized neutron beams are now available at LAMPF (Ref. 10) and SATURNE (Ref. 11) and the search for narrow $I=0$ dibaryon resonances becomes possible.

Using a similar approach we can also apply the diquark-cluster model to the analysis of the strange dibaryon and baryonium. In this article, we present the predictions of the diquark-cluster model for the mass spectrum of low-lying $S=-1$ strange dibaryons and discuss a possible experimental test. (The calculation of the decay width will be discussed in another paper.)

In Sec. II we review the analysis of the diquark-cluster model. In Sec. III, the low-lying mass spectrum of the $S=-1$ strange dibaryons are given together with the spin, parity, isospin, and configuration. We propose in Sec. IV an experimental test to verify this prediction.

II. DIQUARK-CLUSTER MODEL

The details of the diquark-cluster model for nonstrange dibaryons is given in Ref. 1. Here we summarize the major assumptions and problems.

(1) Multiquark systems can be described by the shell model with the jj-coupling scheme as in the nuclear shell model.

(2) A six-quark system consists of three diquarks as illustrated in Fig. 1. When two quarks in a diquark are both in the $1s\frac{1}{2}$ shell, they form a diquark cluster with positive energy.

The mass spectrum of the nonstrange (q^6) system is given by a conventional mass formula in the shell model:

$$M=6m+M(p\tfrac{1}{2})n(p\tfrac{1}{2})+M(p\tfrac{3}{2})n(p\tfrac{3}{2})+M(d\tfrac{3}{2})n(d\tfrac{3}{2})+\delta_3^{12}+\delta_3^{34}+\delta_3^{56}\ , \quad (2.1)$$

where $M(lj)$ is the single-particle excitation energy from a $1s\frac{1}{2}$ shell to the shell with orbital and total angular momenta l and j, respectively, $n(lj)$ is the number of excited quarks in the shell, and δ_3^{ij} the two-particle correlation energy between quarks i and j. The excitation for the shell characterized by $j>\frac{3}{2}$ is neglected. The excitation energy $M(lj)$ is a function of the quark mass m and angular frequency ω and they are taken to be 0.300 GeV (Ref. 1).

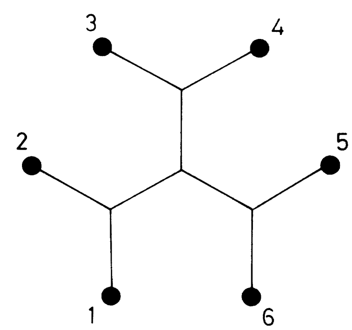

FIG. 1. The color configuration of six quarks in the diquark-cluster model. This system consists of three diquarks (12), (34), and (56). Two quarks in a diquark are tightly bound and make a diquark cluster only in the case where both of them are in $1s\frac{1}{2}$ shell.

For the diquark cluster, the correlation energy δ_3^{ij} is given by

$$\delta_3^{ij} = a + b\mathbf{s}_i \cdot \mathbf{s}_j \ , \tag{2.2}$$

where $\mathbf{s}_i$ is the spin of quark i and the parameters a and b are taken to be 0.1865 and 0.1953 GeV, respectively.[1,2] Generally, the notation $[TS]$ is used for the diquark with isospin T and spin S. In this case, there are two possible diquark clusters [00] and [11] and their respective correlation energies δ_3 are 40 and 235 MeV. We use a notation Δ_{TS} for the correlation energy of the $[TS]$ diquark when one of the constituents is excited to the $1p\frac{1}{2}$ shell. They are given by[1]

$$\begin{aligned} &\Delta_{00} = \Delta_{11} = 0, \quad \Delta_{01} = 10 \text{ MeV} \ , \\ &\Delta_{10} = -60 \text{ MeV} \ . \end{aligned} \tag{2.3}$$

The fact that the [11] diquark cluster is much heavier ($\sim$200 MeV) than the [00] is very important in the diquark-cluster-model analysis. Since the states with no-particle or only a single-particle excitation involve necessarily some [11] diquark clusters, they cannot be the lowest-energy state. The states with a two-particle excitation that do not involve any [11] diquark clusters become the lowest.

The problem in the diquark-cluster model is the mechanism that produces a positive energy for the diquark cluster. Though we cannot answer this question at present, we point out that an idea similar to this diquark-cluster model was introduced recently by other researchers[12–15] in the analysis of very high-energy phenomena. They concluded that the nucleon is a composite system of a quark and a diquark with spin 0,[13,14] which behaves like an elementary particle in the reaction (diquark fragmentation). The relation between the diquark cluster and diquark fragmentation is uncertain at present. However, the deep insight into the mechanism hidden behind them may be one of the most interesting theoretical problems in high-energy physics.

III. THE MASS SPECTRUM OF STRANGE DIBARYONS

Hereafter, we denote the quantities with $S=-1$ by attaching a "prime." For example, the notation m' represents the mass of the s quark. The number of s quarks in a multiquark system is denoted by n_s. Then the strangeness of the system is given by $-n_s$.

The mass formula for the strange dibaryons is given by a simple modification of formulas (2.1) and (2.2):

$$\begin{aligned} M = {} & m(6-n_s) + m'n_s + M(p\tfrac{1}{2})n(p\tfrac{1}{2}) + M(p\tfrac{3}{2})n(p\tfrac{3}{2}) \\ & + M(d\tfrac{3}{2})n(d\tfrac{3}{2}) + M'(p\tfrac{1}{2})n'(p\tfrac{1}{2}) + M'(p\tfrac{3}{2})n'(p\tfrac{3}{2}) \\ & + M'(d\tfrac{3}{2})n'(d\tfrac{3}{2}) + \delta_3^{12} + \delta_3^{34} + \delta_3^{56} \ , \end{aligned} \tag{3.1}$$

where the excitation for the shell characterized by $j > \frac{3}{2}$ is neglected. When a diquark cluster involves an s quark j, the two-particle correlation energy is modified as

$$\delta_3^{ij} = a' + b'\mathbf{s}_i \cdot \mathbf{s}_j' \ . \tag{3.2}$$

Since the parameters b and b' are the expectation value of the color-magnetic interaction between two quarks, there is a relationship

$$b' = \frac{m}{m'} b \ . \tag{3.3}$$

The validity of this formula can be examined by the analysis of the masses of the Λ and Σ particles. Since Λ and Σ are considered to be a composite system of a diquark (1 and 2) and an s quark (3) their masses are given by

$$M_{\Lambda,\Sigma} = 2m + m' + (a + b\mathbf{s}_1 \cdot \mathbf{s}_2) + b'(\mathbf{s}_1 + \mathbf{s}_2) \cdot \mathbf{s}_3' \ , \tag{3.4}$$

where the diquark cluster in Λ and Σ should be [00] and [11], respectively. Taking $m' = 0.476$ GeV, formulas (3.3) and (3.2) give $M_\Lambda = 1.116$ GeV and $M_\Sigma = 1.188$ GeV, which agree well with the experimental values 1.116 and 1.193 GeV.

It is also possible to regard Λ and Σ as a composite system of a strange diquark (1 and 3) and a u or d quark (2). In this picture, formula (3.4) becomes

$$M_{\Lambda,\Sigma} = 2m + m' + (a' + b'\mathbf{s}_1 \cdot \mathbf{s}_3') + b\mathbf{s}_2 \cdot \mathbf{s}_1 + b'\mathbf{s}_2 \cdot \mathbf{s}_3' \ . \tag{3.5}$$

Since (3.4) and (3.5) should give the same mass spectrum, one obtains a relationship

$$a = a' \ . \tag{3.6}$$

The parameters $M'(lj)$ are obtained from the expressions of $M(lj)$ (Ref. 16) by substituting m' and $\sqrt{m/m'}\omega$ for m and ω, respectively. For example,

$$\begin{aligned} &M(p\tfrac{1}{2}) = \omega - \frac{1}{2}\frac{\omega^2}{m} \ , \\ &M'(p\tfrac{1}{2}) = \sqrt{m/m'}\omega - \tfrac{1}{2}\frac{m}{m'^2}\omega^2 \ . \end{aligned} \tag{3.7}$$

There are two possible two-particle correlation energies $\Delta'_{1/2,0}$ and $\Delta'_{1/2,1}$ for the excited strange diquark. Using the method given in Ref. 1, they are estimated to be

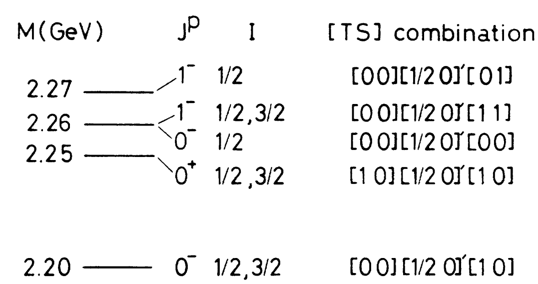

FIG. 2. The mass spectrum of strange dibaryon ($S=-1$). The configurations of negative- and positive-parity states are

$$[(1s\tfrac{1}{2})^2][(1s\tfrac{1}{2})^2]'[(1p\tfrac{1}{2})(1s\tfrac{1}{2})]$$

and

$$[(1p\tfrac{1}{2})(1s\tfrac{1}{2})][(1s\tfrac{1}{2})^2]'[(1p\tfrac{1}{2})(1s\tfrac{1}{2})] \ ,$$

respectively.

-19 and 0 in MeV, respectively.

The $S=-1$ low-lying states[17] below ~ 2.3 GeV are given in Fig. 2, together with the configurations and the [*TS*] combinations of diquarks. As in the nonstrange dibaryons, the states without particle excitation are not the lowest state as they involve at least one [11] diquark cluster. The lowest state is of a single-particle excitation that does not involve a [11] diquark cluster and this is the reason why the lowest state is of negative parity.

The lowest state, which appears at 2.204 GeV, is a $J^P=0^-$ doublet with $I=\frac{1}{2}$ and $\frac{3}{2}$, and this state should be assigned to the candidate of the strange dibaryon observed recently at 2.14 GeV by Piekarz.[18] This seems to be reasonable in the usual sense, but the discrepancy of ~ 60 MeV between the theoretical and the observed values is not small. Though it is very doubtful this discrepancy has a serious physical interpretation, we present one possible speculation. We use the relation (3.6) by reason that the two configurations (diquark)-(strange quark) and (strange diquark)-(quark) are equally weighted. However, as we pointed out in Sec. I, the mechanism of the diquark-cluster formation is still unknown. Thus, it is possible to assume that the former configuration has the strong priority. In such a case, the latter configuration does not exist in Λ and Σ and, therefore, a' becomes a free parameter. If a' is smaller by about 60 MeV than a, then one obtains an agreement between theory and experiment.

We emphasize that the most important result of the diquark-cluster model is that the strange-dibaryon candidate at 2.14 GeV is of $J^P=0^-$. This is different from the conclusion based on the bag model,[19] in which this candidate consists of three states with $J^P=0^-$, 1^-, and 2^- degenerate at a level.

IV. PROPOSAL OF AN EXPERIMENTAL TEST

In this section we propose an experimental test to examine the validity of the conclusions in the previous section. Piekarz[18] found a strange-dibaryon candidate as a peak or shoulder in a missing-mass spectrum of $d(K^-,\pi^-)X$. We examine what will happen if the experiment used a polarized deuteron target $\vec{d}(K^-,\pi^-)X$. The Feynman diagram for the major process is illustrated in Fig. 3. Except trivial kinematic factors, the matrix element for this Feynman diagram is given by

$$m=\int \Psi_B^\dagger(\mathbf{h})m_k(\mathbf{p},\mathbf{q},\mathbf{k})\Psi_d(\mathbf{k})d^3k \ , \tag{4.1}$$

where $\mathbf{p}$ and $\mathbf{q}$ represent the momenta of the incoming K^- meson and the outgoing pion, $\mathbf{k}$ and $\mathbf{h}$ the relative momenta between the neutron and the proton in deuteron and between two baryons in a strange dibaryon, and

$$\mathbf{\Delta}=\mathbf{q}-\mathbf{p}, \quad \mathbf{h}=\mathbf{k}-\frac{\mathbf{\Delta}}{2} \ . \tag{4.2}$$

The terms $\Psi_d(\mathbf{k})$ and $\Psi_B(\mathbf{h})$ represent the deuteron and dibaryon wave function using momentum representation, and m_k is the matrix element for the $K^-+p\rightarrow\pi^- + \Sigma^+$ or $K^-+n\rightarrow\pi^-+\Lambda$, Σ^0 reactions.

Neglecting the *D*-wave component, the deuteron wave function can be written as

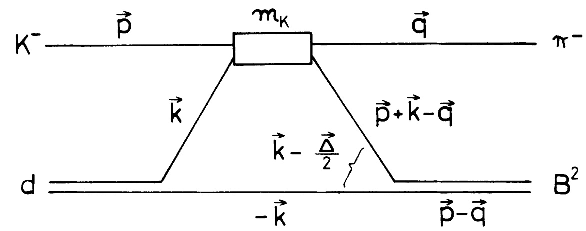

FIG. 3. The Feynman diagram for the $K^-+\mathbf{d}\rightarrow\pi^-+B^2$ reaction.

$$\Psi_d(\mathbf{k})=(\boldsymbol{\eta}\cdot\mathbf{d})\phi(\mathbf{k}) \ , \tag{4.3}$$

where $\mathbf{d}$ represents the spin state using vector representation and η_i $(i=1,2,3)$ are the three bases. The dibaryon wave function is *P* wave and can be written as

$$\Psi_B(\mathbf{h})=\rho_i h_j \varphi(h) \ (i,j=1,2,3) \ , \tag{4.4}$$

The bases ρ_i of spin states and the relative momentum $\mathbf{h}$ do not couple in the bag model while, in the diquark-cluster model, they are combined in a scalar product $\boldsymbol{\rho}\cdot\mathbf{h}$ corresponding to the condition $J=0$ imposed in the state.

The general form of the matrix element m_k is given by

$$m_k=f+i\boldsymbol{\sigma}\cdot\mathbf{n}g \ , \tag{4.5}$$

where $\mathbf{n}$ is a unit vector that is orthogonal to the wave vectors of the incident and scattered waves. The amplitudes f and g are the usual nonflip and spin-flip amplitudes.[20] In the first approximation, they are independent of $\mathbf{k}$ and the vector $\mathbf{n}$ is given by $\mathbf{n}=\mathbf{p}\times\mathbf{q}/|\mathbf{p}\times\mathbf{q}|$. Then the matrix element (4.1) can be written as

$$m\sim[fd_i-g(\mathbf{n}\times\mathbf{d})_i]\Delta_j F(\Delta) \tag{4.6}$$

for the bag model, and

$$m\sim[f(\mathbf{\Delta}\cdot\mathbf{d})-g\mathbf{\Delta}\cdot(\mathbf{n}\times\mathbf{d})]F(\Delta) \tag{4.7}$$

for the diquark-cluster model, where the function $F(\Delta)$ is defined by the formula

$$F(\Delta)=\frac{1}{\Delta^2}\int (\mathbf{h}\cdot\mathbf{\Delta})\varphi^*(h)\phi(k)d^3k \ . \tag{4.8}$$

The probability R of the production of strange dibaryons is proportional to $|m|^2$. By a straightforward calculation using (4.6) and (4.7), one obtains

$$R\propto|f+ign_3|^2+\tfrac{1}{2}|g|^2(1-n_3^2) \tag{4.9}$$

for the bag model, and

$$R\propto|(f+ign_3)(\Delta_1+i\Delta_2)-ig\Delta_3(n_1+in_2)|^2 \tag{4.10}$$

for the diquark-cluster model, where the z axis (3 axis) is taken in the direction $\mathbf{P}$ of the deuteron polarization. Formula (4.9) indicated that in the bag model, R depends on the angle χ between $\mathbf{n}$ and $\mathbf{P}$ alone, i.e.,

$$R\propto|f+ig\cos(\chi)|^2+\tfrac{1}{2}|g|^2\sin^2(\chi) \quad \text{(bag model)} \ . \tag{4.11}$$

Unlike in the bag model, R depends on the direction of

Δ in the diquark-cluster model. To simplify the analysis, we take a special case where **P** is orthogonal to **n**. Then (4.10) can be written as

$$R \propto |f \sin(\xi)+g \cos(\xi)|^2 \quad \text{(diquark-cluster model)}, \tag{4.12}$$

where ξ is the angle between **Δ** and **P** (Fig. 4). In this formula, except for a very special case

$$\frac{g}{f}=\pm i , \tag{4.13}$$

R depends on ξ. We remark that, if condition (4.13) is satisfied, (4.9) and (4.10) can be written as

$$R \propto [1\mp\cos(\chi)]^2+\tfrac{1}{2}\sin^2(\chi) \quad \text{(bag model)}$$

and (4.14)

$$R \propto [1\mp\cos(\chi)]^2 \quad \text{(diquark-cluster model)} .$$

We summarize the results here: (1) If the ξ dependence of R is observed in the geometry shown in Fig. 4, then the diquark-cluster model is favored; (2) when no ξ dependence is observed, the bag model is favored, but the diquark-cluster model cannot be excluded. The reason why the diquark-cluster model is not excluded in the second case is that the following two cases can occur accidentally: (a) Condition (4.13) is satisfied; (b) since two states with $I=\frac{1}{2}$ and $\frac{3}{2}$ are degenerate at this level in the diquark-cluster model, the contributions from these two states cancel the ξ dependence of each other. We note that possibility (a) can be examined experimentally by testing the χ dependence of R given in (4.14).

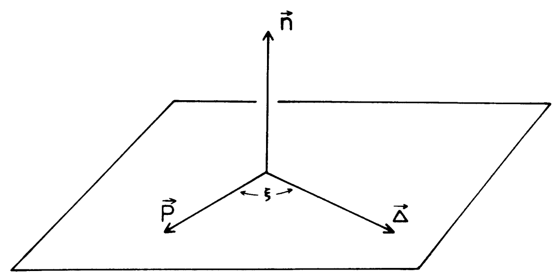

FIG. 4. The definition of angle ξ.

V. CONCLUDING REMARKS

From the observed Δ dependence of the production ratio of strange dibaryons, it is inferred that the strange-dibaryon candidate found by Piekarz is of negative parity. The diquark-cluster model predicts negative parity for it, as does the bag model. The difference between these two models appears in the prediction of the spin state, which was the major subject in this article. The investigation of high-lying states may provide another test for these models. The analysis[21,22] of the lowest strange dibaryon with $S=-2$ (H particle) may be also important in this sense.

Unlike the bag model, the diquark-cluster model is only a semiphenomenological model and, in fact, no explanation has been given for the mechanism of the diquark cluster. In this sense, many strict tests are required to establish its validity. If the experimental evidence supports the diquark-cluster model, the concept of the diquark cluster will play an important role in the construction of a more complete theory.

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[6]B. Tatischeff *et al.*, Phys. Rev. Lett. **52**, 2022 (1984); Report No. IPNO-DRE 86.26, 1986 (unpublished). The latter gives a detailed analysis, again observing three narrow resonances at 2.122, 2.198, and 2.233 GeV. In the previous paper (Ref. 1), we assigned the lowest one to a $J^P=0^+$ state B_2 with a predicted mass 2.08 GeV. However, it might be better to assign these resonances to some of the 1^- or 0^- states with configuration $[(1p\frac{1}{2})(1s\frac{1}{2})]^3$. In fact, the diquark-cluster model predicts that these states are degenerate at three energy levels of approximately 2.13, 2.19, and 2.25 GeV.

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[17]A part of the states with configuration $[(1s\frac{1}{2})^2][(1p\frac{1}{2})(1s\frac{1}{2})]'[(1p\frac{1}{2})(1s\frac{1}{2})]$ lie below 2.3 GeV. In fact, the masses of the states with $[TS]$ combinations $[00][\frac{1}{2}0]'[10]$ ($J^P=0^+$, $I=\frac{1}{2},\frac{3}{2}$) and $[00][\frac{1}{2}1]'[10]$ ($J^P=1^+$, $I=\frac{1}{2},\frac{3}{2}$) are predicted to be 2.27 and 2.29 GeV, respectively. However, we omit these states from Fig. 2 because the predicted masses are not very reliable. This is because, though the masses of these states depend on new parameters $\Delta'_{1/2,0}$ and $\Delta'_{1/2,1}$, within the present method the values of these two parameters cannot be determined unambiguously.

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