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SU(6) prediction of Λ_c branching ratio in B-meson decays

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We study two-body baryonic decays of pseudoscalar B mesons to charmed-baryon–antibaryon pairs, where baryons (or antibaryons) are orbital ground states in spin doublets or quartets. The four-fermion interaction theory forbids F-wave decays for spin-quartet–quartet final-state configurations. SU(6) symmetry requires that all decay amplitudes are expressed by no more than eight parameters: three for S wave, four for P wave, and one for D wave. Both Λ_c inclusive and some exclusive branching ratios are studied based on the assumption of two-body dominance in baryonic decays of B mesons. Results are listed in tables.

In this paper we would like to explore charmed-baryon decays of B mesons from the point of view of SU(6) symmetry.[1] Some analyses based on SU(3) symmetry have already appeared.[2,3] Obviously, SU(6) symmetry, which combines the light-flavor SU(3) with spin, more stringently constrains the decay amplitudes, so it gives more relations among different decay amplitudes than SU(3). The relevance of these relations depends on how small the SU(6)-breaking factors are. SU(3) is a good symmetry if the u-, d-, s-quark mass difference is small compared to the scale of strong interactions (about 1 GeV; Ref. 4) and the coset symmetry SU(6)/SU(3) is good if the energy of the hyperfine interaction[5] is small. Both conditions are well satisfied here; therefore, we believe the SU(6) analysis may give some guide on what is going on in the processes under investigation. We shall limit ourselves here to two-body baryonic decays where a "body" is an S-wave baryon in spin doublet or quartet.

Before going into detail, let us first review some general facts. Now the final states of the baryon-antibaryon pairs may have one of the following spin combinations: (i) $\frac{1}{2}+\frac{1}{2}$; (ii) $\frac{1}{2}+\frac{3}{2}$; (iii) $\frac{3}{2}+\frac{3}{2}$. As is well known, the final angular momentum for (i) can be $L=0$ or 1, since the weak decay B mesons have spin zero. Similarly, for (ii), $L=1$ or 2 and for (iii), $L=0$, 1, 2, or 3. We shall mark these amplitudes as S, P, D, F, respectively, following common conventions. Note that S and D are parity-conserving amplitudes and P and F, parity-violating ones. In the nonrelativistic limit, one neglects D- and F-wave amplitudes; of course, one may recover them if nonrelativistic limit is not valid (and probably this is the case for B-meson decays). It is very interresting to notice that if weak decays are governed by four-quark operators, as they are in the standard model, the F wave does not appear simply because the spin of the four quarks cannot match the F wave to make a scalar. Therefore we only have to establish three kinds of relations: the S-wave relations for (i) and (iii), the P-wave relations for (i), (ii), and (iii) and the D-wave relations for (ii) and (iii).

Expanding a vector or axial-vector current made of a particle-antiparticle pair (e.g., $\bar{u}\gamma_\mu v$) in terms of spin and relevant three-momentum $\mathbf{p}$, we find that the parity-conserving Hamiltonian has the structure

$$H^{\rm PC}\sim 1\otimes 1\oplus \boldsymbol{\sigma}\otimes\boldsymbol{\sigma}\oplus\boldsymbol{\sigma}\cdot\mathbf{p}\otimes\boldsymbol{\sigma}\cdot\mathbf{p}\ , \tag{1}$$

where the first and second terms contribute to S-wave amplitudes and the third, to the S and D waves. Note the second term means that quarks in each currents flip spins but the total spin is conserved. In the third term, the total spin can flip two units to match the D wave. The structure of the parity-violating Hamiltonian is

$$H^{\rm PV}\sim 1\otimes\boldsymbol{\sigma}\oplus\boldsymbol{\sigma}\otimes 1\oplus\boldsymbol{\sigma}\wedge\boldsymbol{\sigma}\ . \tag{2}$$

For SU(6) calculations, only spins of the quarks are relevant. Also, for group-theory calculations, it is convenient to turn the initial B meson into a final-state $\bar{B}$ meson. So the SU(6) Hamiltonian can be written as

$$\begin{aligned}H^{\rm PC}\sim&(b^{\downarrow}\bar{c}^{\uparrow}-b^{\uparrow}\bar{c}^{\downarrow})(\bar{d}^{\uparrow}u^{\downarrow}-\bar{d}^{\downarrow}u^{\uparrow})\\&\oplus[b^{\uparrow}\bar{c}^{\uparrow}\bar{d}^{\downarrow}u^{\downarrow}-\tfrac{1}{2}(b^{\uparrow}\bar{c}^{\downarrow}+b^{\downarrow}\bar{c}^{\uparrow})(\bar{d}^{\downarrow}u^{\uparrow}+\bar{d}^{\uparrow}u^{\downarrow})\\&\quad+b^{\downarrow}\bar{c}^{\downarrow}\bar{d}^{\uparrow}u^{\uparrow}]\oplus b^{\uparrow}\bar{c}^{\uparrow}\bar{d}^{\uparrow}u^{\uparrow}\end{aligned} \tag{3}$$

and

$$\begin{aligned}H^{\rm PV}\sim&(b^{\downarrow}\bar{c}^{\uparrow}-b^{\uparrow}\bar{c}^{\downarrow})\bar{d}^{\uparrow}u^{\uparrow}\\&\oplus b^{\uparrow}\bar{c}^{\uparrow}(\bar{d}^{\uparrow}u^{\downarrow}-\bar{d}^{\downarrow}u^{\uparrow})\\&\oplus b^{\uparrow}\bar{d}^{\uparrow}(\bar{c}^{\uparrow}u^{\downarrow}-\bar{c}^{\downarrow}u^{\uparrow})\ ,\end{aligned} \tag{4}$$

where quark symbols represent creation operators of quarks (e.g., b) or antiquarks ($\bar{c}$). Upper index arrows are the s_z's of the quarks; e.g., $d^{\downarrow}\bar{u}^{\uparrow}-d^{\uparrow}\bar{u}^{\downarrow}$ is a spin-0 combination. Following Ref. 6 we omit color indices, which is equivalent to regarding quarks as bosons. One may imagine terms such as $(b^{\downarrow}\bar{d}^{\uparrow}-b^{\uparrow}\bar{d}^{\downarrow})(u^{\downarrow}\bar{c}^{\uparrow}-u^{\uparrow}\bar{c}^{\downarrow})$ and $(b^{\uparrow}\bar{d}^{\downarrow}-b^{\downarrow}\bar{d}^{\uparrow})\bar{c}^{\uparrow}u^{\uparrow}$. However, they are nothing but specific linear combinations of the first two terms in (3) and three terms in (4), respectively, due to the Fierz reordering rule.

From the SU(6) point of view, the b and c quarks are SU(6) singlets, and the terms in $H^{\rm PC}$ and $H^{\rm PV}$ are members of some 35-plets. As already pointed out, the charmed antibaryons and ordinary baryons are in $\mathbf{21}^*$ and $\mathbf{56}$, respectively, and the $\bar{B}$ mesons, $\mathbf{6}^*$. Group theory tells us

$$\mathbf{6}^*\otimes\mathbf{21}^*=\mathbf{56}^*+\mathbf{70}^* ,$$

$$\mathbf{56}\otimes(\mathbf{56}^*+\mathbf{70}^*)=(\mathbf{1}+\mathbf{35}+\mathbf{405}+\mathbf{2695})+(\mathbf{35}+\mathbf{280}^*+\mathbf{405}+\mathbf{3200}) .$$

Therefore, for each terms in (3) and (4) there are two ways of making SU(6) invariants with the relevant three multiplets of particles. Now let us describe the SU(6) multiplets in terms of quark operators in order to write down the invariant amplitudes. We have

$$\begin{aligned}&6=(u^\uparrow d^\uparrow s^\uparrow u^\downarrow d^\downarrow s^\downarrow) ,\\ &6^*=(-\bar u^\downarrow -\bar d^\downarrow -\bar s^\downarrow \bar u^\uparrow \bar d^\uparrow \bar s^\uparrow) ,\end{aligned}\tag{5}$$

so the 35-plet is expressed as

$$M^i_j=\begin{bmatrix}u^\uparrow\\ d^\uparrow\\ s^\uparrow\\ u_\downarrow\\ d^\downarrow\\ s^\downarrow\end{bmatrix}(-\bar u^\downarrow -\bar d^\downarrow -\bar s^\downarrow \bar u^\uparrow \bar d^\uparrow \bar s^\uparrow)-\tfrac{1}{6}\eta_0' ,\tag{6}$$

where

$$\eta_0'=\tfrac{1}{6}(-\bar u^\downarrow u^\uparrow+\bar u^\uparrow u^\downarrow-\bar d^\downarrow d^\uparrow+\bar d^\uparrow d^\downarrow-\bar s^\downarrow s^\uparrow+\bar s^\uparrow s^\downarrow) .$$

B mesons are

$$\begin{aligned}&C_k^\uparrow=b^\uparrow(-\bar u^\downarrow -\bar d^\downarrow -\bar s^\downarrow \bar u^\uparrow \bar d^\uparrow \bar s^\uparrow) ,\\ &C_k^\downarrow=b^\downarrow(-\bar u^\downarrow -\bar d^\downarrow -\bar s^\downarrow \bar u^\uparrow \bar d^\uparrow \bar s^\uparrow) ,\end{aligned}\tag{7}$$

and we make the phase convention

$$\bar B_u=\frac{1}{2}(b^\downarrow \bar u^\uparrow - b^\uparrow \bar u^\downarrow), \text{ etc.}$$

Charmed antibaryons are

$$\begin{aligned}&A_{jk}^\uparrow=\bar c^\uparrow(-\bar u^\downarrow -\bar d^\downarrow -\bar s^\downarrow \bar u^\uparrow \bar d^\uparrow \bar s^\uparrow)^{\{2\}} ,\\ &A_{jk}^\downarrow=\bar c^\downarrow(-\bar u^\downarrow -\bar d^\downarrow -\bar s^\downarrow \bar u^\uparrow \bar d^\uparrow \bar s^\uparrow)^{\{2\}} ,\end{aligned}\tag{8}$$

and the light baryons made of the u,d,s quarks are

$$B^{ijk}=(u^\uparrow d^\uparrow s^\uparrow u^\downarrow d^\downarrow s^\downarrow)^{\{3\}} ,\tag{9}$$

where

$$(x,y)^{\{2\}}=\begin{bmatrix}xx & xy\\ xy & yy\end{bmatrix}$$

and similarly for $(x,y)^{\{3\}}$. Following general rules of making group invariants we find

$$\begin{aligned}\mathcal{A}^{\rm PC}=&S_1(b^\downarrow\bar c^\uparrow-b^\uparrow\bar c^\downarrow)(M^5{}_4A_{5j}B^{4jk}+M^2{}_1A_{2j}B^{1jk})C_k\\ &+S_2[(-b^\uparrow\bar c^\uparrow)M^2{}_4A_{2j}B^{4jk}-\tfrac{1}{2}(b^\downarrow\bar c^\uparrow+b^\uparrow\bar c^\downarrow)(M^5{}_4A_{5j}B^{4jk}-M^2{}_1A_{2j}B^{1jk})+b^\downarrow\bar c^\downarrow M^5{}_1A_{5j}B^{1jk}]C_k\\ &+S_3(b^\downarrow\bar c^\uparrow-b^\uparrow\bar c^\downarrow)(M^5{}_4C_5B^{4jk}+M^2{}_1C_2B^{1jk})A_{jk}\\ &+S_3'[-b^\uparrow\bar c^\uparrow M^2{}_4C_2B^{4jk}-\tfrac{1}{2}(b^\downarrow\bar c^\uparrow+b^\uparrow\bar c^\downarrow)(M^5{}_4C_5B^{4jk}-M^2{}_1C_2B^{1jk})+b^\downarrow\bar c^\downarrow M^5{}_1C_5B^{1jk}]A_{jk}\\ &+D_1b^\uparrow\bar c^\uparrow M^5{}_1A_{5j}B^{1jk}C_k+D_2b^\uparrow\bar c^\uparrow M^5{}_1C_5B^{1jk}A_{jk} ,\end{aligned}\tag{10}$$

$$\begin{aligned}\mathcal{A}^{\rm PV}=&-P_1b^\uparrow\bar c^\uparrow(M^5{}_4A_{5j}B^{4jk}+M^2{}_1A_{2j}B^{1jk})C_k+\tfrac{3}{2}P_2(b^\downarrow\bar c^\uparrow-b^\uparrow\bar c^\downarrow)M^5{}_1A_{5j}B^{1jk}C_k\\ &-P_3b^\uparrow\bar c^\uparrow(M^5{}_4C_5B^{4jk}+M^2{}_1C_2B^{1jk})A_{jk}-P_3'(b^\downarrow\bar c^\uparrow-b^\uparrow\bar c^\downarrow)M^5{}_1C_5B^{1jk}A_{jk}\\ &+P_4(b^\uparrow\bar c^\uparrow M^5{}_4B^{4jk}-b^\uparrow\bar c^\downarrow M^5{}_1B^{1jk})A_{5j}C_k+P_4'(b^\uparrow\bar c^\uparrow M^5{}_4B^{4jk}-b^\uparrow\bar c^\downarrow M^5{}_1B^{1jk})C_5A_{jk} ,\end{aligned}\tag{11}$$

where S_i, etc., are parameters as explained before. Making use of the rules such as $c^\uparrow A_{ij}=A_{ij}^\uparrow$, etc., we find that S_3' terms are exactly the same as the S_3 terms if only $B(0^-)$ mesons are concerned, so we drop S_3' terms for 0^- decays. Similarly, we drop P_3' and P_4' terms, because they coincide with P_3 terms. In addition, D_2 terms do not contribute to $B_d(0^-)$ decay, so are dropped. Therefore there are eight independent invariant amplitudes for $B(0^-)$ decays, three for S wave, four for P wave, and one D wave. These are listed in Table I where all quarks should be collected to compose light baryons and antiquarks, charmed antibaryons. It is worth noting that each term corresponds to specific quark diagrams: S_3 and P_3 are from exchange diagrams, and the others are from spectator diagrams.

All information available in this model about charmed-baryon decays of B mesons is included in Table I. The next question is how to read this table to find what we want to know about these decays. We may give a list of all the possible initial and final states and their amplitudes; however, it is out of the scope of this paper. Instead, we give Λ_c inclusive branching ratios and some

TABLE I. Eight invariant forms for charmed-baryon decays of B mesons.

Term	Forms
$+S_1$	$(-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{u}^{\downarrow}u^{\downarrow}u^{\uparrow}-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{d}^{\downarrow}u^{\downarrow}d^{\uparrow}-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\downarrow}u^{\downarrow}s^{\uparrow}$ $+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{u}^{\uparrow}u^{\downarrow}u^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{d}^{\uparrow}u^{\downarrow}d^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\uparrow}u^{\downarrow}s^{\downarrow}$ $+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{u}^{\downarrow}u^{\uparrow}u^{\uparrow}+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{d}^{\downarrow}u^{\uparrow}d^{\uparrow}+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{s}^{\downarrow}u^{\uparrow}s^{\uparrow}$ $-\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{u}^{\uparrow}u^{\uparrow}u^{\downarrow}-\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{d}^{\uparrow}u^{\uparrow}d^{\downarrow}-\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{s}^{\uparrow}u^{\uparrow}s^{\downarrow})$ $\times(u^{\downarrow}\bar{B}_u+d^{\downarrow}\bar{B}_d+s^{\downarrow}\bar{B}_s)$ − all spins reversed
$+S_2$	$[(-\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{u}^{\downarrow}u^{\downarrow}u^{\uparrow}-\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{d}^{\downarrow}u^{\downarrow}d^{\uparrow}-\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{s}^{\downarrow}u^{\downarrow}s^{\uparrow}$ $+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{u}^{\uparrow}u^{\downarrow}u^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{d}^{\uparrow}u^{\downarrow}d^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{s}^{\uparrow}u^{\downarrow}s^{\downarrow})$ $-\frac{1}{2}(-\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{u}^{\downarrow}u^{\downarrow}u^{\uparrow}+\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{d}^{\downarrow}u^{\downarrow}d^{\uparrow}+\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{s}^{\downarrow}u^{\downarrow}s^{\uparrow}$ $+\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{u}^{\uparrow}u^{\downarrow}u^{\downarrow}+\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{d}^{\uparrow}u^{\downarrow}d^{\downarrow}+\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{s}^{\uparrow}u^{\downarrow}s^{\downarrow}$ $-\bar{c}^{\downarrow}\bar{d}^{\downarrow}\bar{u}^{\downarrow}u^{\uparrow}u^{\uparrow}-\bar{c}^{\downarrow}\bar{d}^{\downarrow}\bar{d}^{\downarrow}u^{\uparrow}d^{\uparrow}-\bar{c}^{\downarrow}\bar{d}^{\downarrow}\bar{s}^{\downarrow}u^{\uparrow}s^{\uparrow}$ $+\bar{c}^{\downarrow}\bar{d}^{\downarrow}\bar{u}^{\uparrow}u^{\uparrow}u^{\downarrow}+\bar{c}^{\downarrow}\bar{d}^{\downarrow}\bar{d}^{\uparrow}u^{\uparrow}d^{\downarrow}+\bar{c}^{\downarrow}\bar{d}^{\downarrow}\bar{s}^{\uparrow}u^{\uparrow}s^{\downarrow})]$ $\times(u^{\uparrow}\bar{B}_u+d^{\uparrow}\bar{B}_d+s^{\uparrow}\bar{B}_s)$ − all spins reversed
$+S_3$	$(-2\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{d}^{\uparrow}u^{\downarrow}u^{\uparrow}d^{\downarrow}-2\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{d}^{\uparrow}u^{\downarrow}d^{\downarrow}d^{\uparrow}-2\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\downarrow}u^{\downarrow}d^{\downarrow}s^{\uparrow}$ $+2\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{d}^{\uparrow}u^{\downarrow}u^{\downarrow}d^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{d}^{\uparrow}u^{\downarrow}d^{\downarrow}d^{\downarrow}+2\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\uparrow}u^{\downarrow}d^{\downarrow}s^{\downarrow}$ $+2\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{d}^{\downarrow}u^{\downarrow}u^{\uparrow}d^{\uparrow}+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{d}^{\downarrow}u^{\downarrow}d^{\uparrow}d^{\uparrow}+2\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{s}^{\downarrow}u^{\downarrow}d^{\uparrow}s^{\uparrow}$ $-2\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{d}^{\downarrow}u^{\downarrow}u^{\downarrow}d^{\uparrow}-2\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{s}^{\uparrow}u^{\downarrow}d^{\uparrow}s^{\downarrow}$ $+\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{u}^{\downarrow}u^{\downarrow}u^{\uparrow}u^{\uparrow}+2\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{s}^{\downarrow}u^{\downarrow}u^{\uparrow}s^{\uparrow}+\bar{c}^{\uparrow}\bar{s}^{\downarrow}\bar{s}^{\downarrow}u^{\downarrow}s^{\uparrow}s^{\uparrow}$ $-2\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{u}^{\uparrow}u^{\downarrow}u^{\downarrow}u^{\uparrow}-2\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{s}^{\uparrow}u^{\downarrow}u^{\uparrow}s^{\downarrow}-2\bar{c}^{\uparrow}\bar{s}^{\downarrow}\bar{s}^{\uparrow}u^{\downarrow}s^{\uparrow}s^{\downarrow}$ $+\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{u}^{\uparrow}u^{\downarrow}u^{\downarrow}u^{\downarrow}-2\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{s}^{\downarrow}u^{\downarrow}u^{\downarrow}s^{\uparrow}+\bar{c}^{\uparrow}\bar{s}^{\uparrow}\bar{s}^{\uparrow}u^{\downarrow}s^{\downarrow}s^{\downarrow}$ $+2\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{s}^{\uparrow}u^{\downarrow}u^{\downarrow}s^{\downarrow}$ − all spins reversed) $\bar{B}_d$
$-P_1$	$(-\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{d}^{\uparrow}u^{\downarrow}u^{\uparrow}-\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{d}^{\uparrow}u^{\downarrow}d^{\uparrow}-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\downarrow}u^{\downarrow}s^{\uparrow}$ $+\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{d}^{\uparrow}u^{\downarrow}u^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{d}^{\uparrow}u^{\downarrow}d^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\uparrow}u^{\downarrow}s^{\downarrow}$ $+\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{d}^{\downarrow}u^{\uparrow}u^{\uparrow}+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{d}^{\downarrow}u^{\uparrow}d^{\uparrow}+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{s}^{\downarrow}u^{\uparrow}s^{\uparrow}$ $-\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{d}^{\downarrow}u^{\uparrow}u^{\downarrow}-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{d}^{\downarrow}u^{\uparrow}d^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{s}^{\uparrow}u^{\uparrow}s^{\downarrow})$ $\times(u^{\uparrow}\bar{B}_u+d^{\uparrow}\bar{B}_d+s^{\uparrow}\bar{B}_s)$
$\frac{3}{2}P_2$	$(-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{u}^{\downarrow}u^{\uparrow}u^{\uparrow}-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{d}^{\downarrow}u^{\uparrow}d^{\uparrow}-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\downarrow}u^{\uparrow}s^{\uparrow}$ $+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{u}^{\uparrow}u^{\uparrow}u^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{d}^{\uparrow}u^{\uparrow}d^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\uparrow}u^{\uparrow}s^{\downarrow})$ $\times(u^{\downarrow}\bar{B}_u+d^{\downarrow}\bar{B}_d+s^{\downarrow}\bar{B}_s)$ $-(-\bar{c}^{\downarrow}\bar{u}^{\downarrow}\bar{d}^{\uparrow}u^{\uparrow}u^{\uparrow}-\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{d}^{\downarrow}u^{\uparrow}d^{\uparrow}-\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{s}^{\downarrow}u^{\uparrow}s^{\uparrow}$ $+\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{u}^{\uparrow}u^{\uparrow}u^{\downarrow}+\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{d}^{\uparrow}u^{\uparrow}d^{\downarrow}+\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{s}^{\uparrow}u^{\uparrow}s^{\downarrow})$ $\times(u^{\uparrow}\bar{B}_u+d^{\uparrow}\bar{B}_d+s^{\uparrow}\bar{B}_s)$
$-P_3$	$(+2\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{d}^{\downarrow}u^{\uparrow}d^{\uparrow}u^{\uparrow}+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{d}^{\downarrow}u^{\uparrow}d^{\uparrow}d^{\uparrow}+2\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{s}^{\downarrow}u^{\uparrow}d^{\uparrow}s^{\uparrow}$ $-2\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{d}^{\uparrow}u^{\uparrow}u^{\uparrow}d^{\downarrow}-2\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{d}^{\uparrow}u^{\uparrow}d^{\uparrow}d^{\downarrow}-2\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{s}^{\uparrow}u^{\uparrow}d^{\uparrow}s^{\downarrow}$ $-2\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{d}^{\downarrow}u^{\uparrow}u^{\downarrow}d^{\uparrow}+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{d}^{\uparrow}u^{\uparrow}d^{\downarrow}d^{\downarrow}-2\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\downarrow}u^{\uparrow}d^{\downarrow}s^{\uparrow}$ $+2\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{d}^{\uparrow}u^{\downarrow}u^{\uparrow}d^{\downarrow}+2\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\uparrow}u^{\uparrow}d^{\downarrow}s^{\downarrow}$ $+\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{u}^{\downarrow}u^{\uparrow}u^{\uparrow}u^{\uparrow}+2\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{s}^{\downarrow}u^{\uparrow}u^{\uparrow}s^{\uparrow}+\bar{c}^{\uparrow}\bar{s}^{\downarrow}\bar{s}^{\downarrow}u^{\uparrow}s^{\uparrow}s^{\uparrow}$ $-2\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{u}^{\downarrow}u^{\uparrow}u^{\downarrow}u^{\uparrow}-2\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{s}^{\uparrow}u^{\uparrow}u^{\uparrow}s^{\downarrow}-2\bar{c}^{\uparrow}\bar{s}^{\downarrow}\bar{s}^{\uparrow}u^{\uparrow}s^{\downarrow}s^{\uparrow}$ $+\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{u}^{\uparrow}u^{\uparrow}u^{\downarrow}u^{\downarrow}-2\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{s}^{\downarrow}u^{\uparrow}u^{\downarrow}s^{\uparrow}+\bar{c}^{\uparrow}\bar{s}^{\uparrow}\bar{s}^{\uparrow}u^{\uparrow}s^{\downarrow}s^{\downarrow}$ $+2\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{s}^{\uparrow}u^{\uparrow}u^{\downarrow}s^{\downarrow})\bar{B}_d$

TABLE I. (*Continued*).

Term	Forms
P_4	$(-\bar{c}^{\downarrow}\bar{u}^{\downarrow}\bar{d}^{\uparrow}u^{\uparrow}u^{\uparrow}-\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{d}^{\downarrow}u^{\uparrow}d^{\uparrow}-\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{s}^{\downarrow}u^{\uparrow}s^{\uparrow}$ $+\bar{c}^{\downarrow}\bar{u}^{\uparrow}\bar{d}^{\uparrow}u^{\uparrow}u^{\downarrow}+\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{d}^{\uparrow}u^{\uparrow}d^{\downarrow}+\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{s}^{\uparrow}u^{\uparrow}s^{\downarrow}$ $+\bar{c}^{\uparrow}\bar{u}^{\downarrow}\bar{d}^{\uparrow}u^{\downarrow}u^{\uparrow}+\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{d}^{\uparrow}u^{\downarrow}d^{\uparrow}+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\downarrow}u^{\downarrow}s^{\uparrow}$ $-\bar{c}^{\uparrow}\bar{u}^{\uparrow}\bar{d}^{\uparrow}u^{\downarrow}u^{\downarrow}-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{d}^{\uparrow}u^{\downarrow}d^{\downarrow}-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\uparrow}u^{\downarrow}s^{\downarrow})$ $\times(B_u u^{\uparrow}+B_d d^{\uparrow}+B_s s^{\uparrow})$
$+D_1$	$(-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{u}^{\downarrow}u^{\uparrow}u^{\uparrow}-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{d}^{\downarrow}u^{\uparrow}d^{\uparrow}-\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\downarrow}u^{\uparrow}s^{\uparrow}$ $+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{u}^{\uparrow}u^{\uparrow}u^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{d}^{\uparrow}u^{\uparrow}d^{\downarrow}+\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\uparrow}u^{\uparrow}s^{\downarrow})$ $\times(u^{\uparrow}\bar{B}_u+d^{\uparrow}\bar{B}_d+s^{\uparrow}\bar{B}_s)$

exclusive branching ratios such as $B_r(B_d\to\bar{\Lambda}_c P)$. The ARGUS and CLEO Collaborations have separately claimed Λ_c dominance in inclusive baryonic decays from a mixed B_u and B_d decay sample.[7,8]

The inclusive Λ_c fractions in all two-body baryonic decays are very easily estimate by assuming two-body dominance in baryonic decays.[9] From the calculated charmed-baryon spectrum[5] one finds that all charmed baryons of *cuu*, *cdu*, and *cdd* types decay into Λ_c+x by strong or electromagnetic transitions, while charmed baryons of *cds*, *cus*, or *css* types are not allowed to decay into Λ_c because none of them is heavy enough to allow producing K mesons. Based on this observation, our counting indicates that

$$F(B_u\to\bar{\Lambda}_c+X)=\frac{B_u\to\bar{\Lambda}_c+X}{B_u\text{baryonic decays}}=\frac{7}{9}\ , \qquad (12)$$

$$F(B_s\to\bar{\Lambda}_c+X)=\tfrac{2}{3}\ . \qquad (13)$$

It so happens that these inclusive branching ratios are equally valid for S-, P-, and D-wave decay widths. But it is not the case for B_d decays because the Hamiltonian has a $\bar{d}$ quark in it. For the S-wave B_d decays we have [(a,b) is defined as $\frac{1}{2}(a^*b+ab^*)$]

$$F(B_d\to\bar{\Lambda}_c+X)_S\equiv\mathcal{N}_S/\mathcal{D}_S\ ,$$

$$\mathcal{N}_S=15|S_1|^2+\tfrac{47}{4}|S_2|^2+60|S_3|^2$$
$$+24(S_1,S_3)-32(S_2,S_3)-(S_1,S_2)\ , \qquad (14)$$

$$\mathcal{D}_S=19|S_1|^2+\tfrac{59}{4}|S_2|^2+112|S_3|^2$$
$$+32(S_1,S_3)-44(S_2,S_3)-(S_1,S_2)\ .$$

For the P wave we have

$$F(B_d\to\bar{\Lambda}_c+X)P=\mathcal{N}_P/\mathcal{D}_P\ ,$$

$$\mathcal{N}_P=15|P_1|^2+\tfrac{135}{4}|P_2|^2+60|P_3|^2$$
$$+24(P_1,P_3)-36(P_2,P_3)-3(P_1,P_2)$$
$$-14(P_1,P_4)-21(P_2,P_4)+14|P_4|^2\ . \qquad (15)$$

$$\mathcal{D}_P=19|P_1|^2+\tfrac{171}{4}|P_2|^2+112|P_3|^2$$
$$+32(P_1,P_3)-48(P_2,P_3)-3(P_1,P_2)$$
$$-18(P_1,P_4)-27(P_2,P_4)+18|P_4|^2\ .$$

The values of Eqs. (12) to (15) are collected in Table II. A large Λ_c inclusive branching ratio in B_d decay appears when W-exchange diagrams (S_3 and P_3) are neglected.

The story of exclusive branching ratios in B_d to $\bar{\Lambda}_c p$, etc., is much longer. In order to calculate them, let us first give the wave functions of final baryons and antibaryons. The flavor structure of a baryon is classified according to the number of different quark flavors in it. For $n=1$, e.g., *uuu* the wave functions of the baryons are

$$|\Delta^{++},s_z=\tfrac{3}{2}\rangle=\frac{1}{\sqrt{6}}u^{\uparrow}u^{\uparrow}u^{\uparrow}|0\rangle\ ,$$
$$|\Delta^{++},s_z=\tfrac{1}{2}\rangle=\frac{1}{\sqrt{2}}u^{\uparrow}u^{\uparrow}u^{\downarrow}|0\rangle\ . \qquad (16)$$

For $n=2$, let

$$\alpha^{\downarrow}=q_1^{\downarrow}q_1^{\downarrow}q_2^{\uparrow},\ \ \beta^{\downarrow}=q_1^{\uparrow}q_1^{\downarrow}q_2^{\downarrow}\ , \qquad (17)$$

$$M=\alpha-\beta,\ \ S=\alpha+2\beta\ , \qquad (18)$$

TABLE II. Estimated Λ_c fraction in two-body baryonic decays of B mesons.

Meson	$\bar{\Lambda}_c+X$ fraction	Waves
B_u	$\frac{7}{9}$	S,P,D
B_s	$\frac{2}{3}$	S,P,D
B_d	0.54–0.80	S
	0.54–0.86	P
	$\frac{7}{9}$	D

TABLE III. Amplitudes for B mesons to ground-state baryons. P-wave amplitudes are obtained by replacing S_i by P_i. D-wave amplitudes are zero for these modes.

Meson	Baryons	Amplitude			No.
B_u	$\Xi_c^0\Sigma^+$	$-\frac{3}{\sqrt{6}}S_1$	$+\frac{3}{2\sqrt{6}}S_2$		1
B_s	$\overline{\Lambda}_c\Sigma^+$		$\frac{3}{\sqrt{6}}S_2$		2
	$\Xi_c^0\Xi^0$	$\frac{3}{\sqrt{6}}S_1$	$+\frac{3}{2\sqrt{6}}S_2$		3
B_d	$\overline{\Lambda}_c P$		$\frac{3}{\sqrt{6}}S_2$	$-\sqrt{6}S_3$	4
	$\Xi_c^+\Sigma^+$			$-\sqrt{6}S_3$	5
	$\Xi_c^0\Lambda$	$\frac{1}{2}S_1$	$+\frac{3}{4}S_2$	$-S_3$	6
	$\Xi_c^0\Sigma^0$	$\frac{\sqrt{3}}{2}S_1$	$-\frac{\sqrt{3}}{4}S_2$	$+\sqrt{3}S_3$	7
	$\overline{\Omega}_c\Xi^0$			$-2S_3$	8

and, we have, e.g., for uud,

$$|p^{\downarrow}\rangle=\frac{1}{\sqrt{3}}M^{\downarrow}|0\rangle\ , \tag{19}$$

$$|\Delta^{+\downarrow}\rangle=\frac{1}{\sqrt{6}}S^{\downarrow}|0\rangle\ . \tag{20}$$

For $n=3$, let, e.g.,

$$\alpha^{\downarrow}=u^{\uparrow}d^{\downarrow}s^{\downarrow},\ \ \beta^{\downarrow}=u^{\downarrow}d^{\uparrow}s^{\downarrow},\ \ \gamma^{\downarrow}=u^{\downarrow}d^{\downarrow}s^{\uparrow}\ , \tag{21}$$

$$x=\alpha-\beta,\ \ y=\alpha+\beta-2\gamma,\ \ z=\alpha+\beta+\gamma\ , \tag{22}$$

and we have

$$|\Lambda^{\downarrow}\rangle=\frac{1}{\sqrt{2}}x^{\downarrow}|0\rangle,\ \ |\Sigma^{0\downarrow}\rangle=\frac{1}{\sqrt{6}}y^{\downarrow}|0\rangle,\qquad |\Sigma^{0*\downarrow}\rangle=\frac{1}{\sqrt{3}}z^{\downarrow}|0\rangle\ . \tag{23}$$

For charmed antibaryons, we use a, b, and c in place of α, β, and γ, e.g.,

$$a^{\uparrow}=\bar{c}^{\uparrow}\bar{d}^{\uparrow}\bar{s}^{\downarrow},\ \ b^{\uparrow}=\bar{c}^{\uparrow}\bar{d}^{\downarrow}\bar{s}^{\uparrow},\ \ c^{\uparrow}=\bar{c}^{\downarrow}\bar{d}^{\uparrow}\bar{s}^{\uparrow}\ . \tag{24}$$

Our phase convention (in this case, to identify a and b) is made as the following. In a the spin of the lightest quark is $s_z=\frac{1}{2}$. We get $s_z=\frac{1}{2}$ ordinary baryons and $s_z=-\frac{1}{2}$ charmed antibaryons by reversing all spins in (21) and (24), respectively.

The spins of the final baryon-antibaryon pairs are marked by (s,s') where s and s' are the spins of the charmed and ordinary baryons, respectively.

Now we identify each term in Table I according to (m,n) and (s,s'). For s' or s equal to $\frac{1}{2}$, we identify a,b,c or α,β,γ and then express them by M,S (or M',S') according to Eq. (18) if m or $n=2$ and x,y,z (or x',y',z') according to (22) if m or $n=3$. By this way we will find that, for the S-wave amplitudes, there are only $s=s'$ terms with correct coefficients to make the total spin zero. For P-wave amplitudes, $|s-s'|\leq|1$ to make the total spin 1 and, for the D wave, $|s+s'|\geq 2$ to make the total spin 2. In Table III, we give the amplitudes for B mesons to ground-state baryon-antibaryon pairs. These amplitudes satisfy triangle relations given in Ref. 2 from the SU(3) analysis, in particular, since B_u and B_s decays in Table III are governed only by two parameters, we have the triangle relation

$$(B_s\to\Xi_c^0\Xi^0)+(B_u\to\Xi_c^0\Sigma^+)=(B_s\to\overline{\Lambda}_c\Sigma^+)\ . \tag{25}$$

TABLE IV. Fractions of ground-state baryons in baryonic decays of corresponding B mesons. $F=N/D$. For the numbering, see the last column of Table III. (a,b) is defined as $\frac{1}{2}(a^*b+ab^*)$.

No.	wave	N	D	F value
1	S	1	18	$\frac{1}{18}$
	P	$\frac{3}{2}\|P_1-P_2\|^2$	$27[\|P_1\|^2+\frac{9}{4}\|P_2\|^2+\|P_4\|^2$ $-(P_1,P_2)-3(P_2,P_4)$ $+(P_1,P_4)]$	0.0 to 0.06
2,3	S	$\frac{3}{2}[\|S_1\|^2+\frac{5}{4}\|S_2\|^2+(S_1,S_2)]$	$18(\|S_1\|^2+\frac{3}{4}\|S_2\|^2)$	0.08 to 0.17
	P	$\frac{3}{2}[\|P_1\|^2+\frac{5}{4}\|P_2\|^2+(P_1,P_2)]$	$18[\|P_1\|^2+\frac{9}{4}\|P^2\|^2+\|P_4\|^2$ $+(P_1,P_4)-3(P_2,P_4)]$	0.0 to 0.10
4 to 8	S	$\|S_1\|^2+\frac{9}{4}\|S_2\|^2+20\|S_3\|^2$ $-12(S_2,S_3)+2(S_1,S_3)$	$19\|S_1\|^2+\frac{59}{4}\|S_2\|^2$ $+112\|S_3\|^2-44(S_2,S_3)$ $+32(S_1,S_3)-(S_1,S_2)$	0.05 to 0.20
	P	$\|P_1\|^2+\frac{9}{4}\|P_2\|^2+20\|P_3\|^2$ $-12(P_2,P_3)+2(P_1,P_3)$	$19\|P_1\|^2+\frac{171}{4}\|P_2\|^2$ $+112\|P_3\|^2+32(P_1,P_3)$ $-48(P_2,P_3)-3(P_1,P_2)$ $+18\|P_4\|^2-18(P_1,P_4)$ $-27(P_2,P_4)$	0.0 to 0.19

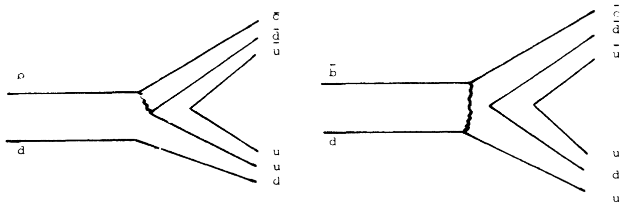

FIG. 1. Quark diagrams of $B_d \to \overline{\Lambda}_c P$ decay.

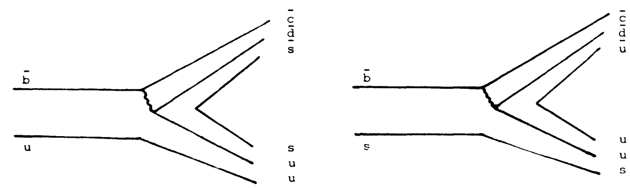

FIG. 2. $E_u \to \Xi_c^0 \Sigma^+$ and $B_S \to \overline{\Lambda}_c \Sigma^+$.

From Table III and the normalization factors in Eqs. (12)–(15) (the parameter dependences of the normalization factors in B_u and B_d decays are accidently canceled out, but the reader can read them off directly from Table I) we obtain Table IV. From this table we find that the typical fraction of one exclusive ground-state baryonic decay mode in baryonic decay channels is about $\frac{1}{20}$, if two-body decays dominate baryonic decays. So its typical branching ratio, taking total baryonic decay branching ratio as, say, larger than 4% into account, is about larger than 2×10^{-3}.

As we stated before, the SU(6) calculation has kind of a correspondence with the quark-diagram calculation,[10] e.g., the S_3 (and P_3) terms are from W-exchange diagrams and the others are from spectator diagrams; see Fig. 1 for $B_d \to \overline{\Lambda}_c p$. Two questions follow. (a) There is only one spectator diagram while there are two SU(6)-invariant coefficients S_1 and S_2 [which is true even if only SU(3) symmetry is considered]; why is this? The reason for this is that, though uud are grouped in the SU(3) octet, the u quark produced at the weak vertex and the d quark can be either in **6** or **3*** and there is no reason to require that the amplitudes for the two cases be equal. (b) From the quark diagrams—see Fig. 2—the amplitudes of $B_u \to \Xi_c^0 \Sigma^+$ and $B_s \to \overline{\Lambda}_c \Sigma^+$ are apparently democratic, but the group-theory calculation tells us that they are not equal; how is this contradiction to be explained? Actually the two modes may be differed by phases and normalization constants, whose evaluation sometimes has to go through all the steps described above, in the section explaining how Table III is obtained. Even for inclusive decays of $B_d \to (\overline{csu})(usu)$ and $B_d \to (\overline{css})(ssu)$, their widths are still different; see S_3 (or P_3) terms in Table I.

The SU(6) analysis is more restrictive than the SU(3) one in a few aspects. First, it minimizes the D-wave invariants to only one, compared to eight in the SU(3) case. Incidently, we ruled out F waves from general considerations at the beginning. Second, it connects amplitudes of different final-state spin configurations. There can be six of them: $(\frac{1}{2}_x,\frac{1}{2})$, $(\frac{1}{2}_y,\frac{1}{2})$, $(\frac{3}{2},\frac{3}{2})$, $(\frac{1}{2}_x,\frac{3}{2})$, $(\frac{1}{2}_y,\frac{3}{2})$, $(\frac{3}{2},\frac{1}{2})$. All these amplitudes are expressed by only eight independent invariants. They would need 30 invariants, if only SU(3) is considered. Finally, our invariants correspond explicitly to different quark diagrams, so they are very convenient for model calculations.

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