B-meson weak decays into baryon-antibaryon pairs in SU(3)

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Using SU(3) symmetry, which we expect to hold well for B-meson decays, we obtain relations among the B-meson weak decays into baryon-antibaryon pairs. It is hoped that in the near future experimental data on these decays will become available and so will provide tests on the assumptions involved.

I. INTRODUCTION

Weak decays are a rich source of information about the form and symmetry of basic interactions. They are essential for testing the standard model and determining the fundamental quark mixing parameters. Their study for heavier hadrons is expected to provide insight on many of the long-standing problems of present-day physics, such as the $\Delta I=\frac{1}{2}$ rule, the interplay of strong and weak interactions, and parity and CP violations. The lowest-lying pseudoscalar bottom mesons B_u, B_d, B_s, and B_c are stable against strong and electromagnetic decays and so decay weakly. Because of their large mass, B mesons can decay weakly [1,2] into baryon-anti-baryon pairs with a significant branching ratio. It will probably take some time to explain, on the basis of QCD, the experimental results when they become available. Therefore, it would be interesting to see what is implied on decay amplitudes, decay rates, and branching ratios by symmetry relations alone. Mesonic decays of B mesons have been studied by several authors [3–6]. The charm-changing weak decays of B mesons into baryon-antibaryon pairs have been considered by Savage and Wise [6].

In this work, we discuss the SU(3)-symmetry implications for charm-conserving weak decays of B mesons into baryon-antibaryon pairs as we expect them to occur with comparable branching ratios. Some of the decay modes of this type ($B\to\Lambda\bar{p}$ and $B\to p\bar{p}$) have been observed [7]. For B-meson decays SU(3) symmetry should hold rather well as it arises from neglecting the SU(3) mass breaking differences between the u, d, and s quarks which are small compared to the relevant momentum scale. The effective weak Hamiltonian is given in Sec. II. Section III deals with the details of the method of calculations. The decay-rate relations for various modes are given in Sec. IV.

II. WEAK HAMILTONIAN

To lowest order in the weak interaction, the nonleptonic weak Hamiltonian H can effectively be written as

$$H_w=\frac{G}{\sqrt{2}}J_\mu J^\mu+\text{H.c.}\ , \tag{1}$$

where the weak current J_μ is given by

$$J_\mu=(\bar{u}\;\bar{c}\;\bar{t})_L(\gamma_\mu)\begin{bmatrix}d'\\ s'\\ b'\end{bmatrix}_L . \tag{2}$$

The weak eigenstates d',s',b' are related [8] to the mass eigenstates d,s,b by

$$\begin{bmatrix}d'\\ s'\\ b'\end{bmatrix}=\begin{bmatrix}V_{ud} & V_{us} & V_{ub}\\ V_{cd} & V_{cs} & V_{cb}\\ V_{td} & V_{ts} & V_{tb}\end{bmatrix}\begin{bmatrix}d\\ s\\ b\end{bmatrix} \tag{3}$$

so that the nonleptonic weak decays involving the decay of the b quark are described by the Hamiltonian

$$\begin{aligned}H=\frac{G}{\sqrt{2}}[\,&V_{ub}V_{cd}^{*}(\bar{u}b)(\bar{d}c)+V_{ub}V_{cs}^{*}(\bar{u}b)(\bar{s}c)\\ &+V_{ub}V_{ud}^{*}(\bar{u}b)(\bar{d}u)+V_{cb}V_{ud}^{*}(\bar{c}b)(\bar{d}u)\\ &+V_{cb}V_{us}^{*}(\bar{c}b)(\bar{s}u)+V_{cb}V_{cs}^{*}(\bar{c}b)(\bar{s}c)\\ &+V_{ub}V_{us}^{*}(\bar{u}b)(\bar{s}u)+V_{cb}V_{cd}^{*}(\bar{c}b)(\bar{d}c)]\ ;\end{aligned} \tag{4}$$

the color and space-time structure is omitted. In the flavor-SU(4) symmetry, the b quark is a singlet. The Hamiltonian for the $\Delta b=-1$ process belongs to the representations **4**, **20′** *, and **36** of SU(4). Further decomposing these SU(4) representations into SU(3) irreducible representations, it is easily seen that the $\Delta c=1$ Hamiltonian transforms as an octet under SU(3) while the $\Delta c=0$ Hamiltonian belongs to the representations **3**, **6***, and **15** and the $\Delta c=-1$ part transforms as $\mathbf{3}+\mathbf{6}$.

We discuss decays with $\Delta b=-1$ and $\Delta c=0$. They arise from the weak Hamiltonian $(b\bar{c})(c\bar{s})$, and so transform as H^4_{34}. We do not write the interaction explicitly in SU(3) for each mode, but write it in SU(4) in general and for different modes work in the SU(3) subspace of SU(4) which is equivalent to working in SU(3), but has the advantage that it allows us to generalize it to SU(4) symmetry rather easily, if we so desire.

III. THE METHOD

We begin by writing the effective Hamiltonian for the B-meson decays in SU(4). Although we make calculations in SU(4) language, we do not use SU(4) symmetry. By taking the appropriate projections, we use SU(3) symmetry as a subgroup of SU(4) for the individual decay modes. This approach has the advantage that it allows us to write the invariants for different SU(3) modes into more compact form, while in SU(3) we will have to write separate invariants for each mode. In addition, we can relate the decays belonging to different SU(3) modes, although in the present work we do not do so.

The weak interaction responsible for the decay of B mesons into baryon-antibaryon pairs belongs to the representations **4**, **20′ ***, and **36** of SU(4) and can be written as

$$H_w^4 = a_1\bar{B}\,{}^a_{[bc]}B_a^{[bc]}P^dH_d + a_2\bar{B}\,{}^e_{[bc]}B_a^{[bc]}P^aH_e + a_3\bar{B}\,{}^a_{[bd]}B_a^{[bc]}P^dH_c \ , \quad (5a)$$

$$H_w^{20'*} = b_1\bar{B}\,{}^a_{[bc]}B_a^{[bd]}P^eH^c_{[de]} + b_2\bar{B}\,{}^a_{[de]}B_a^{[bc]}P^dH^e_{[bc]} + b_3\bar{B}\,{}^d_{[be]}B_a^{[bc]}P^aH^e_{[cd]} + b_4\bar{B}\,{}^d_{[bc]}B_a^{[bc]}P^eH^a_{[de]} + b_5\bar{B}\,{}^d_{[be]}B_a^{[bc]}P^eH^a_{[cd]} \ , \quad (5b)$$

$$H_w^{36} = c_1\bar{B}\,{}^a_{[bc]}B_a^{[bd]}P^eH^c_{(de)} + c_2\bar{B}\,{}^d_{[be]}B_a^{[bc]}P^aH^e_{[cd]} + c_3\bar{B}\,{}^d_{[bc]}B_a^{[bc]}P^eH^a_{(de)} + c_4\bar{B}\,{}^d_{(be)}B_a^{[bc]}P^eH^a_{(cd)} \ , \quad (5c)$$

where the tensor $B_a^{[bd]}$ represents **20′** of ground-state $\frac{1}{2}^+$ baryons, $\bar{B}\,{}^a_{[bc]}$ represents their antiparticles, P^e the four B mesons, and H represents the spurion responsible for the decays. Only H_3, $H^4_{[3,4]}$, and $H^4_{\{3,4\}}$ contribute for the $\Delta c=0$ decays. The ground-state $\frac{1}{2}^+$ baryons belonging to the **20′** representation of SU(4) have the following isospin and SU(3) content:

$$\mathbf{20'}: B(8)\begin{bmatrix} N \\ \Lambda \\ \Sigma \\ \Xi \end{bmatrix} + B(3^*)\begin{bmatrix} \Lambda_c \\ \Xi_c' \end{bmatrix} + B(6)\begin{bmatrix} \Sigma_c \\ \Xi_c \\ \Omega_c \end{bmatrix} + B(3)\begin{bmatrix} \Xi_{cc} \\ \Omega_{cc} \end{bmatrix} ,$$

where the subscript denotes the charm quantum number.

IV. DECAY AMPLITUDES

The decay amplitudes for different modes are calculated in terms of the parameters and are listed in Table I. The decay-rate relations obtained are given below:

(a) $P(3)\to B(8)+\bar{B}(8)$

$$\begin{aligned}
&\Gamma(B_s\to\Lambda\bar{\Sigma}^0)=0 \ , \\
&\Gamma(B_u\to\Sigma^-\bar{n})=2\Gamma(B_u\to\Sigma^0\bar{p})=\Gamma(B_d\to\Sigma^+\bar{p})=2\Gamma(B_d\to\Sigma^0\bar{n}) \ , \\
&\Gamma(B_u\to\Xi^0\bar{\Sigma}^+)=2\Gamma(B_d\to\Xi^0\bar{\Sigma}^0)=\Gamma(B_d\to\Xi^-\bar{\Sigma}^-) \ , \\
&\Gamma(B_u\to\Lambda\bar{p})=\Gamma(B_d\to\Lambda\bar{n}) \ , \\
&\Gamma(B_s\to p\bar{p})=\Gamma(B_s\to n\bar{n}) \ , \\
&\Gamma(B_s\to\Sigma^+\bar{\Sigma}^+)=\Gamma(B_s\to\Sigma^0\bar{\Sigma}^0)=\Gamma(B_s\to\Sigma^-\bar{\Sigma}^-) \ , \\
&\Gamma(B_s\to\Xi^0\bar{\Xi}^0)=\Gamma(B_s\to\Xi^-\bar{\Xi}^-) \ ;
\end{aligned} \quad (6)$$

(b) $B_c\to B(8)+\bar{B}(6)$

$$\begin{aligned}
&\Gamma(B_c\to\Lambda\bar{\Sigma}_c^+)=0 \ , \\
&\Gamma(B_c\to\Sigma^+\bar{\Sigma}_c^{++})=\Gamma(B_c\to\Sigma^0\bar{\Sigma}_c^+)=\Gamma(B_c\to\Sigma^-\bar{\Sigma}_c^0)=2\Gamma(B_c\to\Xi^0\bar{\Xi}_c^+)=2\Gamma(B_c\to\Xi^-\bar{\Xi}_c^0) \ ;
\end{aligned} \quad (7)$$

(c) $B_c\to B(8)+\bar{B}(3^*)$

$$\Gamma(B_c\to\Sigma^0\bar{\Lambda}_c^+)=0 \ , 3\Gamma(B_c\to\Lambda\bar{\Lambda}_c^+)=2\Gamma(B_c\to\Xi^0\bar{\Xi}_c'^+)=2\Gamma(B_c\to\Xi^-\bar{\Xi}_c'^0) \ ; \quad (8)$$

(d) $P(3)\to B(6)+\bar{B}(6)$

$$\begin{aligned}
&\Gamma(B_u\to\Xi_c^+\bar{\Sigma}_c^{++})=2\Gamma(B_u\to\Xi_c^0\bar{\Sigma}_c^+)=2\Gamma(B_u\to\Omega_c^0\bar{\Xi}_c^+) \\
&\qquad =2\Gamma(B_d\to\Xi_c^+\bar{\Sigma}_c^+)=\Gamma(B_u\to\Xi_c^0\bar{\Sigma}_c^0)=\Gamma(B_u\to\Omega_c^0\bar{\Xi}_c^0) \ , \\
&\Gamma(B_s\to\Sigma_c^+\bar{\Sigma}_c^+)=\Gamma(B_s\to\Sigma_c^0\bar{\Sigma}_c^0)=\Gamma(B_s\to\Sigma_c^{++}\bar{\Sigma}_c^{++}) \ , \\
&\Gamma(B_s\to\Xi_c^+\bar{\Xi}_c^+)=\Gamma(B_s\to\Xi_c^0\bar{\Xi}_c^0) \ ;
\end{aligned} \quad (9)$$

TABLE I. The following are for the modes $[H(^{4}_{34})]$ $\Delta c=0$, $\Delta b=0$, $\Delta I=0$. Each decay has an overall factor of $V_{cb}V_{cs}=(C_1C_2S_3+S_2C_3e^{i\delta})(C_1C_2S_3-S_2C_3e^{i\delta})$, where $C_i=\cos\theta i$, $S_i=\sin\theta i$.

Decay	
	(a) $\mathbf{3\to8+8}$
$B_u\to\Lambda\bar{p}$	$-(1/\sqrt{6})(2A_2-A_1)$
$\to\Sigma^0\bar{p}$	$(1/\sqrt{2})A_1$
$\to\Sigma^-\bar{n}$	A_1
$\to\Xi^0\bar{\Sigma}^+$	A_2
$\to\Xi^-\bar{\Lambda}$	$(1/\sqrt{6})(-A_2+2A_1)$
$\to\Xi^-\bar{\Sigma}^0$	$-(1/\sqrt{2})A_2$
$B_d\to\Lambda\bar{n}$	$-(1/\sqrt{6})(2A_2-A_1)$
$\to\Sigma^+\bar{p}$	A_1
$\to\Sigma^0\bar{n}$	$(1/\sqrt{2})A_1$
$\to\Xi^0\bar{\Lambda}$	$(1/\sqrt{6})(A_2-2A_1)$
$\to\Xi^0\bar{\Sigma}^0$	$-(1/\sqrt{2})A_2$
$\to\Xi^-\bar{\Sigma}^-$	$-A_2$
$B_s\to p\bar{p}$	A_1+A_3
$\to n\bar{n}$	A_1+A_3
$\to\Lambda\bar{\Lambda}$	$(2/3)(2A_1+2A_2+3A_3)$
$\to\Lambda\bar{\Sigma}^0$	0
$\to\Sigma^+\bar{\Sigma}^+$	$2A_3$
$\to\Sigma^0\bar{\Sigma}^0$	$2A_3$
$\to\Sigma^-\bar{\Sigma}^-$	$2A_3$
$\to\Xi^0\bar{\Xi}^0$	A_2+A_3
$\to\Xi^-\bar{\Xi}^-$	A_2+A_3
	(b) $\mathbf{3\to8+\bar{6}}$
$B_c\to\Lambda\bar{\Sigma}_c^+$	0
$\to\Sigma^+\bar{\Sigma}_c^{++}$	B
$\to\Sigma^0\bar{\Sigma}_c^+$	B
$\to\Sigma^-\bar{\Sigma}_c^0$	B
$\to\Xi^0\bar{\Xi}_c^+$	$\frac{-1}{\sqrt{2}}B$
$\to\Xi^-\bar{\Xi}_c^0$	$\frac{-1}{\sqrt{2}}B$
	(c) $\mathbf{1\to8+\bar{3}^*}$
$B_c\to\Lambda\bar{\Lambda}_c^+$	$\frac{-1}{3}C$
$\to\Sigma^0\bar{\Lambda}_c^+$	0
$\to\Xi^0\bar{\Xi}_c^{+\prime}$	$\frac{1}{\sqrt{2}}C$
$\to\Xi^-\bar{\Xi}_c^{0\prime}$	$\frac{1}{\sqrt{6}}C$
	(d) $\mathbf{3\to6+\bar{6}}$
$B_u\to\Xi_c^+\bar{\Sigma}_c^{++}$	$\frac{-1}{\sqrt{2}}D_1$
$\to\Xi_c^0\bar{\Sigma}_c^+$	$\frac{1}{2}D_1$
$\to\Omega_c^0\bar{\Xi}_c^+$	$\frac{1}{2}D_1$
$B_d\to\Xi_c^0\bar{\Sigma}_c^+$	$\frac{1}{2}D_1$
$\to\Xi_c^0\bar{\Sigma}_c^0$	$\frac{1}{\sqrt{2}}D_1$
$\to\Omega_c^0\bar{\Xi}_c^0$	$\frac{1}{\sqrt{2}}D_1$
$B_s\to\Sigma_c^+\bar{\Sigma}_c^+$	D_2
$\to\Sigma_c^0\bar{\Sigma}_c^0$	D_2
$\to\Xi_c^+\bar{\Xi}_c^+$	D_1+2D_2
$\to\Xi_c^0\bar{\Xi}_c^0$	D_1+2D_2
$\to\Omega_c^0\bar{\Omega}_c^0$	D_1+D_2
$\to\Sigma_c^{++}\bar{\Sigma}_c^{++}$	D_2

Decay	
	(e) $\mathbf{3\to6+\bar{3}^*}$
$B_u\to\Xi_c^0\bar{\Lambda}_c^+$	$\frac{1}{2\sqrt{3}}E$
$\to\Omega_c^0\bar{\Xi}_c^{+\prime}$	$\frac{-1}{\sqrt{6}}E$
$B_d\to\Xi_c^+\bar{\Lambda}_c^+$	$\frac{-1}{2\sqrt{3}}E$
$\to\Omega_c^0\bar{\Xi}_c^{0\prime}$	$\frac{-1}{\sqrt{6}}E$
$B_s\to\Sigma_c^+\bar{\Lambda}_c^+$	0
$\to\Xi_c^+\bar{\Xi}_c^{+\prime}$	$\frac{1}{2\sqrt{3}}E$
$\to\Xi_c^0\bar{\Xi}_c^{0\prime}$	$\frac{1}{2\sqrt{3}}E$
	(f) $\mathbf{1\to6+\bar{3}}$
$B_c\to\Xi_c^+\bar{\Xi}_{cc}^{++}$	$\frac{2}{\sqrt{2}}F$
$\to\Xi_c^0\bar{\Xi}_{cc}^+$	$\frac{2}{\sqrt{2}}F$
$\to\Omega_c^0\bar{\Omega}_{cc}^+$	$2F$
	(g) $\mathbf{3\to3^*+\bar{6}}$
$B_u\to\Xi_c^{+\prime}\bar{\Sigma}_c^{++}$	$\frac{1}{\sqrt{6}}G$
$\to\Xi_c^{0\prime}\bar{\Sigma}_c^+$	$-\frac{1}{\sqrt{3}}G$
$B_d\to\Xi_c^{+\prime}\bar{\Sigma}_c^+$	$-\frac{1}{2\sqrt{3}}G$
$\to\Xi_c^{0\prime}\bar{\Sigma}_c^0$	$-\frac{1}{\sqrt{6}}G$
$B_s\to\Xi_c^{+\prime}\bar{\Xi}_c^+$	$-\frac{1}{2\sqrt{3}}G$
$\to\Xi_c^{0\prime}\bar{\Xi}_c^0$	$-\frac{1}{2\sqrt{3}}G$
$\to\Lambda_c^+\bar{\Sigma}_c^0$	0
	(h) $\mathbf{3\to3^*+\bar{3}^*}$
$B_u\to\Xi_c^{0\prime}\bar{\Lambda}_c^+$	$-\frac{1}{6}H_1$
$B_d\to\Xi_c^{+\prime}\bar{\Lambda}_c^+$	$\frac{1}{6}H_1$
$B_s\to\Xi_c^{+\prime}\bar{\Xi}_c^{+\prime}$	$\frac{1}{6}(H_2-H_1)$
$\to\Xi_c^{0\prime}\bar{\Xi}_c^{0\prime}$	$\frac{1}{6}(H_2-H_1)$
$\to\Lambda_c\bar{\Lambda}_c^+$	$\frac{1}{6}A_2$
	(i) $\mathbf{1\to3^*+\bar{3}}$
$B_c\to\Xi_c^{+\prime}\bar{\Xi}_{cc}^{++}$	$\frac{2}{\sqrt{6}}I$
$\to\Xi_c^{0\prime}\bar{\Xi}_{cc}^+$	$\frac{2}{\sqrt{6}}I$
	(j) $\mathbf{3\to3+\bar{3}}$
$B_u\to\Omega_{cc}^+\bar{\Xi}_{cc}^{++}$	J_1
$B_d\to\Omega_{cc}^+\bar{\Xi}_{cc}^{++}$	J_1
$B_s\to\Xi_{cc}^{++}\bar{\Xi}_{cc}^+$	J_2-J_1
$\to\Xi_{cc}^+\bar{\Xi}_{cc}^+$	J_2-J_1
$\to\Omega_{cc}^+\bar{\Omega}_{cc}^+$	J_2

(e) $P(3)\to B(6)+\bar{B}(3^*)$

$$\Gamma(B_c\to\Sigma_c^+\bar{\Lambda}_c^+)=0\ ,$$
$$\Gamma(B_u\to\Omega_c^0\bar{\Xi}_c'^+)=2\Gamma(B_u\to\Xi_c^0\bar{\Lambda}_c^+)=2\Gamma(B_d\to\Xi_c^0\bar{\Lambda}_c^+)$$
$$=\Gamma(B_d\to\Omega_c^0\bar{\Xi}_c'^0)=2\Gamma(B_s\to\Xi_c^+\bar{\Xi}_c'^+)=2\Gamma(B_s\to\Xi_c^0\bar{\Xi}_c'^0)\ ; \tag{10}$$

(f) $B_c\to B(6)+\bar{B}(3)$

$$\Gamma(B_c\to\Omega_c^0\bar{\Omega}_{cc}^+)=2\Gamma(B_c\to\Xi_c^+\bar{\Xi}_{cc}^{++})=2\Gamma(B_c\to\Xi_c^0\bar{\Xi}_{cc}^+)\ ; \tag{11}$$

(g) $P(3)\to B(3^*)+\bar{B}(6)$

$$\Gamma(B_d\to\bar{\Lambda}_c^+\Sigma_c^0)=0\ ,$$
$$\Gamma(B_u\to\Xi_c'^0\bar{\Sigma}_c^+)=2\Gamma(B_u\to\Xi_c'^+\bar{\Sigma}_c^{++})$$
$$=4\Gamma(B_d\to\Xi_c'^+\bar{\Sigma}_c^+)=2\Gamma(B_d\to\Xi_c'^0\bar{\Sigma}_c^0)$$
$$=4\Gamma(B_s\to\Xi_c'^+\bar{\Xi}_c^+)=4\Gamma(B_s\to\Xi_c'^0\bar{\Xi}_c^0)\ ; \tag{12}$$

(h) $P(3)\to B(3^*)+\bar{B}(3^*)$

$$\Gamma(B_u\to\Xi_c'^0\bar{\Lambda}_c^+)=\Gamma(B_d\to\Xi_c'^+\bar{\Lambda}_c^+)=\Gamma(B_s\to\Lambda_c^+\bar{\Lambda}_c^+)\ , \tag{13}$$
$$\Gamma(B_s\to\Xi_c'^+\bar{\Xi}_c'^+)=\Gamma(B_s\to\Xi_c'^0\bar{\Xi}_c'^0)\ ;$$

(i) $B_c\to B(3^*)+\bar{B}(3)$

$$\Gamma(B_c\to\Xi_c'^+\bar{\Xi}_{cc}^{++})=\Gamma(B_c\to\Xi_c'^0\bar{\Xi}_{cc}^+)\ ; \tag{14}$$

(j) $P(3)\to B(3)+\bar{B}(3)$

$$\Gamma(B_u\to\Omega_{cc}^+\bar{\Xi}_{cc}^{++})=\Gamma(B_d\to\Omega_{cc}^+\bar{\Xi}_{cc}^+)\ ,$$
$$\Gamma(B_s\to\Xi_{cc}^{++}\bar{\Xi}_{cc}^{++})=\Gamma(B_s\to\Xi_{cc}^+\bar{\Xi}_{cc}^+)\ . \tag{15}$$

In the tables drawn from the point of view of SU(3), we have expressed the decay amplitudes in terms of SU(3) parameters. They are related to the SU(4) parameters by

$$A_1=a_3\ ,$$
$$A_2=2a_2-b_3+c_2\ ,$$
$$A_3=2a_1-b_1-c_1\ ,$$
$$B=a_3+b_1+c_1\ ,$$
$$C=4a_2-a_3-b_1-2b_3+4b_4-2b_5-c_1+2c_2+4c_3+2c_4\ ,$$
$$D_1=2a_2-a_3\ ,$$
$$D_2=2a_1+a_3\ ,$$
$$E=2a_2+a_3+2b_5-2c_4\ ,$$
$$F=a_2+b_4+c_3\ ,$$
$$G=-2a_2-a_3+2b_3+2c_2\ ,$$
$$H_1=-2a_2+5a_3+2b_3+2b_5+2c_2+6c_4\ ,$$
$$H_2=12a_1+6a_3-4b_1-8b_4+4b_5+4c_1+8c_3+4c_4\ ,$$
$$I=a_2-a_3-b_1-b_3+b_4-b_5+c_1+c_2-c_3+c_4\ ,$$
$$J_1=-a_3-b_5-c_4\ ,$$
$$J_2=2a_1-2b_4+2c_3\ .$$

In the limit of exact SU(3), which we believe would be valid in the case of B-meson decays, we have obtained relations between the decay rates of baryon-antibaryon pairs. The two-body decays $B_u\to\Lambda\bar{p}$ and $B_d\to p\bar{p}$ have been seen and their upper limit are listed by the Particle Data Group [8]. We expect that in the near future more decay modes will be measured and will provide a test for the standard model.

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