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Lawrence Radiation Laboratory
Berkeley, California

Contract No. W-7405-eng-48

NOTES ON ANTIBARYON INTERACTIONS

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July 29, 1959

Printed for the U. S. Atomic Energy Commission

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This note presents some simple consequences of (or checks for) invariance considerations as applied to interactions of antibaryons.

A. P conservation in strong interactions. Consider the reactions $\bar{p} + p \rightarrow n$ particles. If the reaction occurs at rest for $n \geqslant 4$ or in flight for $n \geqslant 3$, there are enough independent momentum vectors to form, in any coordinate system, a nonvanishing quantity $\vec{p}_1 \cdot (\vec{p}_2 \times \vec{p}_3)$. The condition of symmetry in the up-down distribution of $\vec{p}_1$ relative to the (p_2, p_3) plane is then a consequence of P conservation, unless other inherent symmetries require this distribution to be symmetrical anyway. Thus, consider the reaction in flight

$$\bar{p} + p \rightarrow 1 + 2 + R \ , \qquad (1)$$

where 1 and 2 are some specific particles and where the "rest" R may be any assembly of particles. We always work in the $(\bar{p}, p)$-c.m. system and consider exclusively unpolarized beams and targets. The initial state is in general not an eigenstate of P. But it is an eigenstate of PR, where R is a 180° rotation around any axis perpendicular to $(\bar{p}, p)$ and which we may take perpendicular to $(\bar{p}, 1)$. Let $W(1, E_1, \theta_1; \ 2, E_2, \theta_2, \phi)$

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denote the probability of finding particle 1(2) with an energy $E_1(E_2)$ at an angle $\theta_1(\theta_2)$ relative to the direction of $\bar{p}$, where ϕ is the azimuth of 2 relative to the $(\bar{p},\ 1)$ plane. Then PR implies

$$W(1,\ E_1,\ \theta_1;\ 2,\ E_2,\ \theta_2,\ \phi) = W(1,\ E_1,\ \theta_1;\ 2,\ E_2,\ \theta_2,\ -\phi). \tag{2}$$

As an example of other symmetries which would imply Eq. (2), we note that if 1 and 2 are both π^+, Eq. (2) is valid as a consequence of Bose statistics. If one considers the triple $(\bar{p},\ \pi_+,\ \pi_-)$, however, there seems to be no other known symmetry than PR which leads to Eq. (2).

B. C invariance of strong interactions. Consider again Reaction (1) and also

$$\bar{p} + p \rightarrow \bar{1} + \bar{2} + \bar{R}\ . \tag{3}$$

[The products in Reaction (3) may or may not be identical with those of Reaction (1).] The initial state ψ_S (S = 0, 1 is the total spin) is in general not an eigenstate of C. However, we have

$$CR\ \psi_S = (-1)^S\ \psi_S\ , \tag{4}$$

which makes CR useful for an unpolarized beam and target, as here the cross section for any reaction does not involve any singlet-triplet interference so that, for no initial polarization, CR invariance may be applied to the final states. Let the probabilities referring to Eq. (2) be denoted by $\bar{W}$. Then CR implies

$$W(1,\ E_1,\ \theta_1;\ 2,\ E_2,\ \theta_2,\ \phi) = \bar{W}(\bar{1},\ E_1,\ \pi - \theta_1;\ \bar{2},\ E_2,\ \pi - \theta_2,\ \pi - \phi)\ . \tag{5}$$

In the case of pure pion annihilation the symbols $\overline{W}$ and W refer to the same reaction. In other instances, such as $\overline{p} + p \rightarrow \overline{p} + \Lambda + K_+$, $\overline{p} + p \rightarrow p + \overline{\Lambda} + K_-$, they refer to different reactions.

We may also apply CP to the final states, as

$$CP\ \psi_S = (-1)^{S+1}\ \psi_S \ , \tag{6}$$

and obtain

$$W(1,\ E_1,\ \theta_1;\ 2,\ E_2,\ \theta_2,\ \phi) = \overline{W}(\overline{1},\ E_1,\ \pi - \theta_1;\ \overline{2},\ E_2,\ \pi - \theta_2,\ \pi + \phi) \ . \tag{7}$$

Equations (2), (5), and (7) are derived channel by channel. They may therefore also be applied to sums over channels so that there are no complications because of incomplete knowledge of the neutral particles produced.

Whenever P conservation is established, one may check C by using a relation that, in itself, follows either from CR or from CP, such as

$$W(1,\ E,\ \theta) = \overline{W}(\overline{1},\ E,\ \pi - \theta) \ . \tag{8}$$

From this relation it follows that the π_o distribution in any channel is symmetric around 90^o.

Because antinucleons play a virtual role in low-energy nuclear phenomena, the high degree to which P conservation is known to hold in the latter domain has implications also for these antiparticles. In this sense, relations like Eqs. (2), (5), and (7) may be considered as a useful complement to the low-energy information. Their applicability to very-high-energy phenomena (regardless of the complexity of the events) makes it possible to verify the validity of these conservation laws at frequencies that are perhaps not as sensitively explored in the low-energy nuclear effects.

For two-body reactions like

$$\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda , \tag{9}$$

Eqs. (5) and (7) are trivial. However, here CP also has a useful application. If we denote by $\vec{q}(\Lambda, \theta)$ and $\vec{q}(\bar{\Lambda}, \theta)$ respectively the polarizations of Λ and $\bar{\Lambda}$, if any, where θ is the angle between the particle in question and the $\bar{p}$ direction, then CP implies

$$\vec{q}(\Lambda, \theta) = \vec{q}(\bar{\Lambda}, \pi - \theta) . \tag{10}$$

(Of course P implies more stringently that the $\vec{q}$ vectors are perpendicular to the production plane.) Equation (6) is here also valid in the final state, so that the differential cross section of Eq. (9) is the sum of a triplet-triplet and a singlet-singlet differential cross section. Furthermore it is readily shown that Eq. (10) also applies generally if $\vec{q}(\Lambda, \theta)$ refers to Reaction (1) and $\vec{q}(\bar{\Lambda}, \theta)$ to (3), again as a consequence of CP. Thus Eq. (10) holds for $(\bar{\Lambda}, \Sigma_0)$ as compared to $(\Lambda, \bar{\Sigma}_0)$ production; the partial cross sections of these reactions should be each others mirror around 90°.

C. Charge symmetry (CS) and charge independence (CI). Antihyperon annihilations via strong interactions provide in principle various means to verify CS and CI. In practice, large numbers of antihyperon events are needed for this.[1]

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[1] Thus for $\bar{\Lambda}$ production in hydrogen by 1-Bev antiprotons, one would need to have an annihilation cross section as large as ~ 50 mb to have an effect $\sim 1\%$.

For $(\bar{\Lambda}, p)$ annihilation, we have[2] from CI

$$(\bar{\Lambda}, p \rightarrow K_0, \pi_+) = 2(\bar{\Lambda}, p \rightarrow K_+, \pi_0) . \qquad (11)$$

This is the only relation that CI imposes.[3] A much more interesting situation obtains if the $\bar{\Lambda}$'s are annihilated in deuterium. The reason is that the $(\bar{\Lambda}, d)$ system is self-charge symmetric. (It shares this property with (Λ, d), but it has considerable phase-space advantage.) Thus let $W(K_+)$ and $W(K_0)$ be the probabilities, respectively, of producing a $K_+(K_0)$ in $(\bar{\Lambda}, d)$ annihilation. Then CS tells us[2]

$$W(K_+) = W(K_0) , \qquad (12)$$

regardless of the complexity of the various annihilation modes possible.[4] Thus $(\bar{\Lambda}, d)$ interactions may be of particular interest at very high energies. In addition, we have[5] from CI

$$(\bar{\Lambda}, d \rightarrow n, K_+, \pi_0) = \frac{1}{4} (\bar{\Lambda}, d \rightarrow n, K_0, \pi_+) . \qquad (13)$$

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2 The relations (11) to (17) refer to relative rates and are valid for all energies and all angles.

3 In this note, we do not consider inequalities following from CI.

4 Of course Eq. (12) may also be applied to an individual channel and its charge symmetric one, such as (n, K_0, π_+) versus (p, K_+, π_-), etc.

5. Here the pure $I = 1$ state of the K-nucleon system is involved. In $(\bar{\Lambda}, d \rightarrow p, K_0) = (\bar{\Lambda}, d \rightarrow n, K_+)$ we deal with the corresponding pure $I = 0$ state.

The annihilation in flight of $\overline{\Sigma}_{\pm}$ in d also tests CS. Call $W_{\pm}(K)$ the probability of producing a K in $\overline{\Sigma}_{\pm}$ - d reactions. Then we have

$$W_{\pm}(K_{+}) = W_{\mp}(K_{o}) \quad . \tag{14}$$

Finally, production reactions in d yield a few CI relations, namely:

$$(\overline{p}, d \to \overline{\Lambda}, \Lambda, p, \pi_{-}) = 2(\overline{p}, d \to \overline{\Lambda}, \Lambda, n, \pi_{o}) \tag{15}$$

$$(\overline{p}, d \to \overline{\Sigma}_{+}, \Lambda, p) = 2(\overline{p}, d \to \overline{\Sigma}_{o}, \Lambda, n) \tag{16}$$

$$(\overline{p}, d \to \overline{\Lambda}, \Sigma_{-}, p) = 2(\overline{p}, d \to \overline{\Lambda}, \Sigma_{o}, n) \quad . \tag{17}$$

D. $\overline{\Lambda}$ decay and T invariance. It has been noted by Okubo[6] that CPT-invariance by itself does not imply the equality of the partial lifetimes of hyperon decay into a given channel and of antihyperon decay into the corresponding charge-conjugate channel. In general there are three independent sufficient grounds for two such quantities to be equal, namely (a) absence of final-state interactions, (b) C invariance, and (c) T invariance. In the case of the $\overline{\Lambda}$, there is a fourth independent sufficient ground, namely the $\Delta I = \frac{1}{2}$ rule.[7] Thus the validity of the latter rule would obviate the possibility of testing T invariance by means of a partial lifetime comparison. This is in principle not the case when one compares the up-down asymmetries α_{ch} and $\overline{\alpha}_{ch}$ of the decays $\Lambda \to p + \pi_{-}$ and $\overline{\Lambda} \to \overline{p} + \pi_{+}$. In fact, if one assumes the

6. S. Okubo, Phys. Rev. 109, 984 (1958).

7 Electromagnetic effects are ignored here.

$\Delta I = \frac{1}{2}$ rule to be valid, one has

$$\rho \equiv \alpha_{ch}/\bar{\alpha}_{ch} = \frac{\sin(\delta_{11} - \delta_1 - \Delta)}{\sin(\delta_{11} - \delta_1 + \Delta)} \quad , \tag{18}$$

where δ_{11} and δ_1 are the $P_{1/2}$ and $S_{1/2}$ π-nucleon phase shifts in the $I = \frac{1}{2}$ state. Here Δ has the following properties: If C invariance holds, we have $\Delta = 0$, so $\rho = 1$; if T invariance holds, we have $\Delta = \pi/2$, so $\rho = -1$. From the magnitude of α_{ch} we know already[8] that $|\Delta| \gtrsim \pi/4$. We also see that $\rho = -1$ if $\delta_{11} - \delta_1$ is neglected relative to Δ. As this neglect is justified to a good approximation, it follows that a 20% deviation from $\rho = -1$ is the most that can be anticipated.[9]

I am indebted to many physicists at the Lawrence Radiation Laboratory for stimulating discussions.

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8 R. Gatto, Phys. Rev. 108, 1103 (1957); cf. also S. Weinberg, Phys. Rev. 110, 782 (1958).

9 Putting $\Delta = \pi/2 - \epsilon$, $\rho \simeq -(1 + 0,2 \cdot \mathrm{tg}\epsilon)$.