Some Implications of Higher Symmetries*

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Spin correlation effects in baryon-baryon scattering are discussed as tests for the existence of "higher" symmetries in strong interaction physics. It is shown that the detection of certain characteristic correlations could serve to rule out at once whole classes of potential higher symmetry candidates. Other sorts of testable effects, which bear on particular models of higher symmetry under current discussion, are also briefly described.

IN discussing the notion of approximate symmetries[1–8] which go beyond isotopic spin invariance, one naturally thinks first in terms of grouping particles and resonances into appropriate multiplets and then relating cross sections for otherwise distinct reactions.[9] But it can also happen that symmetry principles imply definite restrictions which are internal to a single, given reaction. This is illustrated by the familiar example of elastic neutron-proton scattering, where isotopic spin conservation implies an absence of mixing between singlet and triplet spin states. We wish here to enlarge on just this example, for the general case of baryon-baryon (or baryon-antibaryon) scattering. The point will be that the experimental detection of certain characteristic effects can serve to rule out at once whole classes of possible higher symmetries.

Consider the reaction

$$a+b\rightarrow c+d \tag{1}$$

among four, possibly distinct, spin-$\frac{1}{2}$ objects. We accept time-reversal invariance and parity conservation and suppose that the product of the intrinsic parities of the particles concerned is even. In the general case, eight distinct scalar functions of center-of-mass energy and scattering angle are needed to characterize the reaction. To see this, recall that for definite total angular momentum j a system of two spin-$\frac{1}{2}$ objects can take on orbital and spin angular momentum quantum numbers given by the sets $(l,s)=(j+1,\,1)$, $(j,1)$, $(j-1,\,1)$ and $(j,0)$. For definite j there are eight distinct transitions $(l,s)\rightarrow(l',s')$ consistent with the parity conservation requirement $(-1)^{l+l'}=1$. Let us denote the corresponding partial-wave amplitudes by the symbols $f(l',s';l,s)$.

Now, for certain familiar situations we know that, in fact, there are fewer than eight independent amplitudes. For example, in the case of elastic scattering, with, say, $a=c$ and $b=d$, time-reversal invariance guarantees that

$$f(j+1,\,1;\,j-1,\,1)=f(j-1,\,1;\,j+1,\,1)\,, \tag{A1}$$

$$f(j,1;\,j,0)=f(j,0;\,j,1)\,. \tag{A2}$$

On the other hand, if $a=b$ and $c=d$, then the Pauli principle guarantees that

$$f(j,1;\,j,0)=f(j,0;\,j,1)=0\,. \tag{B}$$

But if higher symmetries are operative, these restrictions acquire a more general validity and can thus serve as an experimental test for whole classes of possible symmetries. The situation can be summarized in the following way.

(A) Suppose that the strong interactions are invariant under a certain group of transformations such that a and c belong to a common irreducible representation, and b and d belong to another, possibly distinct, irreducible representation. Moreover, suppose that the direct product of the two irreducible representations in question is simply reducible, i.e., that no irreducible representation in the decomposition of the direct product occurs with multiplicity greater than one. Then the over all scattering amplitude must be a unique sum of purely elastic amplitudes labeled by the irreducible representations in the direct product; and time-reversal invariance then leads to the restrictions (A) given above. As a special case, it is clear that the restrictions (A) follow if there is a symmetry operation which, among other things, leads to the simultaneous transformations $a\rightleftarrows c$ and $b\rightleftarrows d$.

Consider for example the reaction

$$\bar{p}+p\rightarrow\bar{\Sigma}^-+\Sigma^+\,. \tag{2}$$

The restrictions (A1) are here not expected to hold on the basis of any well-established symmetry principles.

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However, in the octet model of $SU(3)$ symmetry,[1] the strong interactions are supposed to be invariant under a group of transformations which, among other things, leads to the interchanges $p \rightleftarrows \Sigma^+$,[10] and on this model the restriction (A1) becomes applicable. [The restrictions (B), hence (A2), are automatic here by the Pauli principle.]

(B) Next consider the possibility that the strong interactions are invariant under some group of transformations, with respect to which a and b belong to one common irreducible representation, c and d to another, possibly distinct, irreducible representation. This time suppose that the direct product with itself of the a $(=b)$ representation is simply reducible, and similarly for the direct product of the c $(=d)$ representation with itself. The net scattering amplitude is then a sum of terms, labeled by the common irreducible representations, and additional quantum numbers, each of which has definite parity with respect to permutations; and the restrictions (B) then follow from the Pauli principle. Once again, it is clear as a special case that (B) follows if there is a symmetry operation which, among other things, leads to the simultaneous transformations $a \rightleftarrows b$, $c \rightleftarrows d$.

Consider the example

$$\bar{\Sigma}^+ + n \rightarrow \Sigma^+ + \bar{\Xi}^0. \tag{3}$$

There is no well-established symmetry principle which guarantees the restrictions (B) for this reaction. However, in the octet model of $SU(3)$ there is a group of transformations which, among other things, produces the interchanges[10] $\Sigma^- \rightleftarrows n$ and $\Sigma^+ \rightleftarrows \Xi^0$. This, together with charge conjugation invariance, leads to the restrictions (B) in question. As another example, we mention the reaction

$$\Sigma^+ + p \rightarrow \Sigma^+ + p. \tag{3$'$}$$

Here the conditions (A) automatically follow from time-reversal invariance. The conditions (B), however, are not general, but would follow from invariance under $\Sigma^+ \rightleftarrows p$, as in the octet model.

Further nontrivial illustrations of the restrictions (A) and (B) could be written down, not only for the octet model of $SU(3)$ but also for other symmetry schemes currently under discussion, e.g., those involving the groups G_2,[3] O_5,[7] R symmetry,[1,4] etc.[11] There is no need here to give an exhaustive listing, which in any case depends not only on the group in question but also on the way the baryons are assigned to available irreducible representations. The general point to be emphasized, however, is that an observed violation of (A) or (B), for various baryon-baryon or baryon-antibaryon reactions, could serve to rule out at once whole classes of potential symmetry schemes.

[10] C. A. Levinson, H. J. Lipkin, and S. Meshkov, Phys. Letters **1**, 44 (1962).

[11] Consider the reaction $p+\Xi^- \rightarrow \Lambda^0+\Lambda^0$. Many of the symmetry models which have been discussed (Refs. 3–7) postulate an invariance under $p \rightleftarrows \Xi^-$, $\Lambda \rightleftarrows \Lambda$. This entails the restrictions (B).

The more practical question is how the effects in question could be measured. What is involved, clearly, is a matter of polarization correlations.[12] If the polarizations of all four of the reacting particles could be measured, there would be no difficulty, but this is perhaps visionary. Concerning the outgoing particles, however, it is fortunate that some of the baryons $(\Lambda,\Sigma^0,\Sigma^+,\Xi^-,\Xi^0)$ serve as their own polarization analyzers via parity violation in weak decays. Luckily, the measurement of polarization correlations for the outgoing particles alone is enough to detect whether condition (B) is violated; so, for example, the following would be among the especially interesting reactions [as it happens, the octet $SU(3)$ model in particular does not bear on them, though other symmetry schemes do]:

$$\Xi^- + p \rightarrow \Lambda^0+\Lambda^0,\ \Sigma^0+\Sigma^0,\ \Sigma^0+\Lambda^0,\ \text{etc.}$$
$$\bar{p}+n \rightarrow \bar{\Sigma}^-+\Lambda^0,\ \bar{\Sigma}^-+\Sigma^0,\ \text{etc.}$$

and the practically more difficult reaction (3) is available for testing $SU(3)$.

Let us denote by $\mathbf{k}$ and $\mathbf{k}'$ the unit vectors along the initial and final momenta in the center-of-mass system of the collision; and introduce, for convenience, an orthonormal set of vectors based on these according to

$$\mathbf{K}=\frac{\mathbf{k}'-\mathbf{k}}{|\mathbf{k}'-\mathbf{k}|},\quad \mathbf{P}=\frac{\mathbf{k}'+\mathbf{k}}{|\mathbf{k}'+\mathbf{k}|},\quad \mathbf{n}=\frac{\mathbf{k}\times\mathbf{k}'}{|\mathbf{k}\times\mathbf{k}'|}. \tag{4}$$

Introducing Pauli spinors χ, we write the over-all scattering amplitude

$$f=\chi_c{}^\dagger\chi_d{}^\dagger g\chi_a\chi_b, \tag{5}$$

where the operator g takes, most generally, the form

$$\begin{aligned} g=A+B(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\mathbf{n}+C\boldsymbol{\sigma}_1\cdot\mathbf{K}\boldsymbol{\sigma}_2\cdot\mathbf{K}+D\boldsymbol{\sigma}_1\cdot\mathbf{P}\boldsymbol{\sigma}_2\cdot\mathbf{P} \\ +E\boldsymbol{\sigma}_1\cdot\mathbf{n}\boldsymbol{\sigma}_2\cdot\mathbf{n}+F_1(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot\mathbf{n}+iF_2(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\cdot\mathbf{n} \\ +F_3(\boldsymbol{\sigma}_1\cdot\mathbf{P}\boldsymbol{\sigma}_2\cdot\mathbf{K}+\boldsymbol{\sigma}_1\cdot\mathbf{K}\boldsymbol{\sigma}_2\cdot\mathbf{P}). \end{aligned} \tag{6}$$

The Pauli matrices $\boldsymbol{\sigma}_1$ act, say, between the spinors for particles a and c; and $\boldsymbol{\sigma}_2$ acts between b and d. The coefficient functions A, B, C, $\cdots$ depend on energy and scattering angle.

It is evident that the restrictions (A) are equivalent to invariance of g under $\boldsymbol{\sigma}\rightarrow-\boldsymbol{\sigma}$ and $\mathbf{k}\rightleftarrows\mathbf{k}'$. So the restrictions (A) are equivalent to

$$F_2=F_3=0. \tag{A$'$}$$

On the other hand, the terms unsymmetric under $\boldsymbol{\sigma}_1 \rightleftarrows \boldsymbol{\sigma}_2$ are clearly responsible for singlet-triplet mixing; hence, the restrictions (B) are equivalent to

$$F_1=F_2=0. \tag{B$'$}$$

Notice that $F_2=0$ is common to both sets of restrictions (A) and (B), i.e., the detection of the F_2 term would throw out symmetries leading to either set.

[12] L. Michel, Nuovo Cimento **22**, 203 (1961); E. DeRafael, *ibid.* **25**, 320 (1962). These authors relate spin-correlation effects for *different* reactions on the basis of symmetries.

For definite initial and final spin states, the differential scattering cross section is given by

$$d\sigma/d\Omega=|f|^2,$$

and a definite formula, which fully displays all spin correlations, could be written down. However, it will be enough here to consider two special cases.

(i) Suppose that the colliding particles are unpolarized but that the polarizations of the outgoing particles can be determined (e.g., via asymmetric weak decays). The density matrix in final spins is then

$$\rho=\tfrac{1}{4}gg^\dagger,$$

and this takes on the form

$$\rho=a_1+a_2(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\cdot\mathbf{n}+a_3\boldsymbol{\sigma}_1\cdot\mathbf{K}\boldsymbol{\sigma}_2\cdot\mathbf{K}+a_4\boldsymbol{\sigma}_1\cdot\mathbf{P}\boldsymbol{\sigma}_2\cdot\mathbf{P} +a_5\boldsymbol{\sigma}_1\cdot\mathbf{n}\boldsymbol{\sigma}_2\cdot\mathbf{n}+a_6(\boldsymbol{\sigma}_1\cdot\mathbf{P}\boldsymbol{\sigma}_2\cdot\mathbf{K}+\boldsymbol{\sigma}_1\cdot\mathbf{K}\boldsymbol{\sigma}_2\cdot\mathbf{P}) +a_7(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)\cdot\mathbf{n}+a_8(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\cdot\mathbf{n}, \quad (7)$$

where the coefficient functions a_i depend on the original functions A, B, C, $\cdots$ in a definite way. For present purposes it is enough to note the following: The terms with coefficient functions a_1 through a_6 are "normal" in that they could be present even if the conditions (A′) and (B′) are satisfied. The interesting terms a_7 and a_8 do not depend on F_3, but if *either* $F_1\neq 0$ or $F_2\neq 0$ then *both* a_7 and a_8 will, in general, be nonvanishing. In other words, the detection of correlations given by the a_7 or a_8 terms would show that either $F_1\neq 0$ or $F_2\neq 0$, or both, hence, that the condition (B) is certainly violated.

If the polarizations are to be measured by observation of asymmetries in the weak decay of the outgoing baryons, one analyzes the decay distributions as follows. Let $\mathbf{p}_c$ and $\mathbf{p}_d$ be unit vectors along say the momentum vectors of the daughter pions, as measured in the rest frames of the corresponding baryons c and d; and let α_c and α_d be the respective decay asymmetry parameters. The differential cross section for the baryon-baryon reaction, regarded as a function of directions of $\mathbf{k}'$, $\mathbf{p}_c$, and $\mathbf{p}_d$, is then given by

$$d\sigma=w(\mathbf{k}',\mathbf{p}_c,\mathbf{p}_d)d\Omega_{\mathbf{k}'}d\Omega_{\mathbf{p}_c}d\Omega_{\mathbf{p}_d} \quad (8)$$

with

$$w=\mathrm{Tr}\rho(1+\alpha_c\boldsymbol{\sigma}_1\cdot\mathbf{p}_c)(1+\alpha_d\boldsymbol{\sigma}_2\cdot\mathbf{p}_d); \quad (9)$$

and one finds

$$w=a_1+a_2(\alpha_c\mathbf{p}_c+\alpha_d\mathbf{p}_d)\cdot\mathbf{n}+\alpha_c\alpha_d \times\{a_3\mathbf{p}_c\cdot\mathbf{K}\mathbf{p}_d\cdot\mathbf{K}+a_4\mathbf{p}_c\cdot\mathbf{P}\mathbf{p}_d\cdot\mathbf{P} +a_5\mathbf{p}_c\cdot\mathbf{n}\mathbf{p}_d\cdot\mathbf{n}+a_6(\mathbf{p}_c\cdot\mathbf{P}\mathbf{p}_d\cdot\mathbf{K}+\mathbf{p}_c\cdot\mathbf{K}\mathbf{p}_d\cdot\mathbf{P})\} +a_7(\alpha_c\mathbf{p}_c-\alpha_d\mathbf{p}_d)\cdot\mathbf{n}+a_8\alpha_c\alpha_d(\mathbf{p}_c\times\mathbf{p}_d)\cdot\mathbf{n}. \quad (10)$$

(ii) Where it is feasible to measure the polarization of only one of the outgoing baryons, it becomes necessary in the present context to employ polarization for at least one of the incoming baryons. So we consider here the case where one of the incident baryons has a measured polarization $\boldsymbol{\Sigma}$, and we ask for the density matrix in spin for one of the outgoing baryons. This takes on the form

$$\rho=b_1+b_2\boldsymbol{\Sigma}\cdot\mathbf{n}+b_3\boldsymbol{\sigma}\cdot\mathbf{n}+b_4\boldsymbol{\Sigma}\cdot\mathbf{K}\boldsymbol{\sigma}\cdot\mathbf{K}+b_5\boldsymbol{\Sigma}\cdot\mathbf{P}\boldsymbol{\sigma}\cdot\mathbf{P} +b_6\boldsymbol{\Sigma}\cdot\mathbf{n}\boldsymbol{\sigma}\cdot\mathbf{n}+b_7(\boldsymbol{\Sigma}\times\boldsymbol{\sigma})\cdot\mathbf{n} +b_8(\boldsymbol{\Sigma}\cdot\mathbf{P}\boldsymbol{\sigma}\cdot\mathbf{K}+\boldsymbol{\Sigma}\cdot\mathbf{K}\boldsymbol{\sigma}\cdot\mathbf{P}).$$

In this case all of the terms b_1 through b_7 could be nonvanishing even if the restrictions (A′) and (B′) were both met. The interesting term, b_8, could be nonvanishing, however, only if *any* one of the coefficient functions F_1, F_2, F_3 differs from zero; i.e., the detection of the b_8 term would imply that one or another of the sets (A) and (B) is invalidated.

Some practical difficulties have to be mentioned here, and these can be illustrated with the following example. Suppose we consider the reaction

$$\Sigma^++p\rightarrow\Sigma^++p,$$

in which the target proton is unpolarized. If the projectile particle Σ^+ is produced in a simple reaction such as $\pi^++p\rightarrow\Sigma^++K^+$, its polarization $\boldsymbol{\Sigma}$ would be normal to the production plane, hence, normal to the vector $\mathbf{k}$ for the baryon-baryon collision. But then we have $\boldsymbol{\Sigma}\cdot\mathbf{K}=-\boldsymbol{\Sigma}\cdot\mathbf{P}$, and the interesting term b_8 cannot be uniquely distinguished from other terms. So for the class of measurements under discussion the initial polarization vector $\boldsymbol{\Sigma}$ has to be "adjustable"; i.e., either the laboratory target particle has to be polarized, as distinct from the projectile particle, or else the latter has to be correlated with aspects of the production reaction from which it emerges other than just the normal to the production plane.

The notion of testing for higher symmetries with respect to a single reaction can be extended beyond the considerations given here for polarization effects in baryon-baryon scattering. It will suffice here to give a few illustrations.

(1) Consider the reaction

$$\Xi^-+p\rightarrow\Lambda^0+\Sigma^0,$$

but look apart now from polarization effects. In a number of models which have recently been discussed[3–7] there exists a symmetry operation which, among other things, interchanges p and Ξ^-, leaving Λ^0 and Σ^0 unchanged up to algebraic sign. This implies that the scattering amplitude has definite signature under $\Xi^-\rightleftarrows p$, hence, that the differential scattering cross section, averaged over spins, must have forward-backward symmetry in the center-of-mass system.

(2) Next, consider the reaction

$$\pi^-+p\rightarrow\Lambda^0+K^0+\pi^0.$$

Some of the models under current discussion (e.g.,[3] those involving the group G_2) entail invariance under a subgroup of transformations like those of isotopic spin,[13] but with K^0 and π^0 belonging here to a common triplet

[13] See S. Meshkov, C. A. Levinson, and H. J. Lipkin, Phys. Rev. Letters **10**, 361 (1963). Their discussion can easily be extended to groups other than $SU(3)$.

[("I","I_z")=(1,1) for K_0; (1,0) for π^0]. With respect to the same subgroup, π^- has the quantum numbers $(\frac{1}{2},\frac{1}{2})$, p the quantum numbers $(\frac{1}{2},\frac{1}{2})$, and for Λ^0 one has (0,0). It then follows that the $(K^0\pi^0)$ system in this reaction is uniquely in an "I"=1 state, hence, that the reaction amplitude is purely antisymmetric under $K^0 \rightleftarrows \pi^0$. But this means that the differential cross section must be symmetric under interchange of the K^0 and π^0 momentum vectors.

(3) Similarly, consider the reaction

$$\gamma+p \to Y_1^{-*}+K^++\pi^+.$$

In the octet model of $SU(3)$ one can define a subgroup[13,14] similar to the one discussed under (2). With respect to this subgroup, K^+ and π^+ belong to a common doublet [("I","I_z")=$(\frac{1}{2},\frac{1}{2})$ for K^+; $(\frac{1}{2},-\frac{1}{2})$ for π^+]; p has the quantum numbers $(\frac{1}{2},\frac{1}{2})$, the 1385-MeV resonance Y_1^{-*}, supposedly belonging to the representation ten,[15] has the quantum numbers $(\frac{3}{2},\frac{1}{2})$, and the photon transforms like a scalar (0,0). Therefore, the $(K^+\pi^+)$ system in this reaction is in a pure "I"=1 state, hence, the reaction amplitude is symmetric under $K^+ \rightleftarrows \pi^+$.

[14] N. Cabibbo and R. Gatto, Nuovo Cimento **21**, 872 (1961).

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Search for Ferromagnetically Trapped Magnetic Monopoles of Cosmic-Ray Origin*

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Magnetic monopoles, if they exist, should be trapped and accumulated in ferromagnetic materials. Using the high field of a pulsed magnet, we have sought to extract monopoles from a magnetite outcrop on the earth's surface and from fragments of a stony-iron meteorite. In the nuclear emulsions used for detection, no tracks were found satisfying our geometric criteria and having an energy-loss rate compatible with the theoretical expectation for monopoles. The area-time product of the magnetite cosmic-ray exposure is estimated to be about 10^{13} cm^2 sec. From the negative results, upper-limit monopole production cross sections in the atmosphere are estimated as a function of assumed monopole mass.

1. INTRODUCTION

THIS paper describes a search for magnetic monopoles of cosmic-ray origin. The sensitivity to monopoles incident in the primary cosmic radiation or created in the atmosphere by primary particles is about one-thousand-fold greater than in a previous cosmic-ray experiment of Malkus.[1] The total primary proton flux effective in our experiment is two orders of magnitude less than the proton flux in the accelerator experiment of Purcell *et al.*[2] However, our negative results usefully supplement this and other recent accelerator experiments[3,4] because of the possibility that the monopole is present as a primary cosmic-ray particle and/or the possibility that the monopole mass exceeds 2.9 BeV, the maximum that the accelerator experiments could have revealed.

Because of the anticipated scarcity of monopoles, our experiment, like earlier ones, was designed to detect a single monopole. Such sensitivity is not difficult to achieve if the monopole indeed carries the Dirac quantum of magnetic charge, $g_0=68.5e$, for in that case the monopole can readily be accelerated to high energy in a moderate magnetic field, and in traversing the

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