Polarization Effects in Σ^- Capture

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The interaction of very slow, or captured, polarized Σ^- hyperons with protons, $\Sigma^-+p\rightarrow\Lambda^0+n$, may be used to yield information concerning the parity of Σ relative to Λ, the (Σ, Λ) parity. A qualitative distinction between even and odd parity depends on whether or not the polarization of the emergent Λ's varies with angle of emission. In order to determine the parity unambiguously it would furthermore be necessary to know whether the reaction proceeds from an initial S or P state. Aside from these questions, the polarization of the emergent Λ's serves as a detector of the initial Σ polarization. For example, if Σ's produced under given circumstances do not show an appreciable up-down asymmetry in decay, the above reaction might help to decide whether this is due to negligible polarization of the Σ^- in production.

I. INTRODUCTION

A LARGE up-down asymmetry has recently been observed in Λ decay.[1] The qualitative implications of this result for the weak hyperon-decay interactions are well known[2]; and the actual magnitude of the effect is bound to give us more specific information on the dynamics of these decays.[3] Of course, the effect in question tells us that the Λ's were produced (in π^--p collisions) with a sizable polarization to begin with. Thus a new tool for the study of the dynamics of strong interactions has now become available: the use, where possible, of a strong hyperon-producing reaction as a polarizer and a subsequent hyperon decay as an analyzer. It is the purpose of this note to show how such a situation may be of help in determining the relative parity of Σ and Λ hyperons.

As is well known, the nonconservation of parity leads to a loss of information concerning the parity of Σ, Λ, and K particles relative to nucleon-pion-photon systems. Even so, there are certain relative parities which on the one hand are well defined if parity is conserved in all strong reactions but which on the other hand have not yet been determined unambiguously. As the three independent relative parities that are at stake we can take for example: Σ relative to Λ, K relative to Λ and nucleon, and Ξ relative to nucleon. It is the first one that will concern us here.[4] We shall call this relative parity the (Σ,Λ) parity.

In order to obtain information about this it is suggested to study the reaction

$$\Sigma^-+p\rightarrow\Lambda^0+n, \tag{1}$$

where the Σ^- is polarized and the interaction takes place either from a bound (Σ^-,p) state or at very low energies in the continuum. For a given initial orbital state, the polarization pattern of the emerging Λ depends in a qualitative way on the (Σ,Λ) parity. This can be seen as follows.[5]

If the Σ^- is bound to the proton in a Bohr orbit, we need in practice only be concerned with initial S or P states. (There are, of course, various such states, triplet or singlet and with appropriate j values. A more detailed consideration which takes due account of this is deferred until the next section.) If the reaction occurs for low energies in the continuum, the process (1) will take place predominantly from an S state. In either case, if the initial state is S, then the final state is $S(P)$ for even (odd) (Σ,Λ) parity[6]; if the initial state is P then we go to $P(S)$ in the even (odd) case. Denote the polarization of Σ and Λ by $\mathbf{p}_\Sigma$ and $\mathbf{p}_\Lambda$, respectively ($|\mathbf{p}|=1$ corresponds to complete polarization). The most general relation between these two vector quantities can then be summarized as follows:

$$\left.\begin{array}{ll}\text{(even)} & S\rightarrow S\\ \text{(odd)} & P\rightarrow S\end{array}\right\}\mathbf{p}_\Lambda=a\mathbf{p}_\Sigma, \tag{2}$$

$$\left.\begin{array}{ll}\text{(even)} & P\rightarrow P\\ \text{(odd)} & S\rightarrow P\end{array}\right\}\mathbf{p}_\Lambda=a\mathbf{p}_\Sigma+b(\mathbf{p}_\Sigma\cdot\mathbf{N})\mathbf{N}. \tag{3}$$

Here $\mathbf{N}$ is the unit vector in the direction of motion of the emitted Λ particle. These equations state the obvious fact that a dependence of $\mathbf{p}_\Lambda$ on $\mathbf{N}$ cannot occur if the final state is an S state.

[1] F. S. Crawford *et al.*, Phys. Rev. **108**, 1102 (1957); F. Eisler *et al.*, Phys. Rev. **108**, 1353 (1957).

[2] See, for example, T. D. Lee *et al.*, Phys. Rev. **106**, 1367 (1957).

[3] The asymmetry is expressed by an angular distribution $1+a\cos\theta$, where θ is the angle between the direction of the decay pion and the direction of Λ polarization (in the Λ-rest system). The parameter a is found to have absolute value 0.51 ± 0.15. (This is a mean parameter over an energy range of the produced Λ's.) The intrinsic decay parameter must be larger than a, as the initial polarization need not be 100%. In terms of an effective decay coupling $\bar{\psi}_\Lambda(1+r\gamma_5)\psi_p\phi_\pi$ this means that the number r is of the order 10, as $r=1$ corresponds to $a\approx v_p/c\approx0.09$. It is interesting to note that a coupling $\bar{\psi}_\Lambda(1+\gamma_5)\gamma_\mu\psi_p\partial\phi_\pi/\partial x_\mu$ can be recast in the above nonderivative form with $r=(M_\Lambda+M_p)$. $(M_\Lambda-M_p)^{-1}\approx12$. This would correspond to $a=0.85$ for 100% polarization.

[4] In the spirit of present views on particle multiplets we assume throughout that members of a given multiplet have relatively even parity.

[5] In what follows, the Σ and the Λ spin are taken to be $\frac{1}{2}$.

[6] It seems reasonable to neglect D admixture to S and F admixtures to P.

Suppose that we knew the initial orbital state. Then if a dependence of Λ polarization on the angle of emission were observed, one would know the (Σ,Λ) parity. If $\mathbf{p}_\Lambda$ were found to be independent of angle, there would be a strong presumption as to this parity, although one would not be quite as certain as in the previous case: the relative value of the constants a and b depends on dynamical details which unfortunately seem for the present beyond theoretical reach. A distribution (3) with $b \ll a$ could simulate a purely isotropic one.

In any case, the situation would be very much sharpened if we knew from which initial orbital state the reaction takes place. Here a comparison of the total rates of the reaction (1) and of

$$\Sigma^- + p \rightarrow \Sigma^0 + n \tag{4}$$

may be of interest. The phase space ratio of the processes (1) and (4) is as 3:1. Now if the reaction occurs in the low-energy continuum we are dealing with an $S\rightarrow S$ transition. If the initial system is bound, it is either an $S\rightarrow S$ or a $P\rightarrow P$ transition.[4] In the latter case it is the comparison of the sum total rate of Λ and Σ^0 production from the $2P$ state with the $2P\rightarrow 1S$ radiative transition rate which decides whether both reactions go predominantly from an S or from a P state. If we then assume that the Λ and the Σ^0 couplings involved are of comparable strengths and are not strongly isotopic spin dependent we have the following possibilities: (1) (Σ^0: $S\rightarrow S$), (Λ^0: $S\rightarrow S$): Λ^0 and Σ^0 produced in comparable numbers, Λ^0 being somewhat favored by phase volume. (2) (Σ^0: $S\rightarrow S$), (Λ^0: $S\rightarrow p$): Σ^0 somewhat favored relative to Λ^0 production, owing to centrifugal barrier effects. (3) (Σ^0: $P\rightarrow P$): Λ^0 strongly favored relative to Σ^0 production, the more so if the (Σ,Λ) parity is odd.

Thus it may be possible to learn from these rates which initial state predominates. By elaborating precisely this kind of argument it has in fact been suggested[7] on the basis of very limited statistics[8] that production mainly takes place from the S-state continuum. If this could be firmly established, the parity determination would become quite unambiguous. At any rate, one sees that the present methods require, from independent considerations, the additional piece of information concerning the initial orbital state.

In this connection, we may note that the reaction (4) in itself can in principle be used to provide this extra information. The polarization $\mathbf{p}_{\Sigma^0}$ of the Σ^0 emitted in reaction (4) is again expressed by equations like (2) and (3), but now there are only the two alternatives, $S\rightarrow S$ and $P\rightarrow P$. Thus if it were possible to determine whether or not $\mathbf{p}_{\Sigma^0}$ depends on angle of emission, one could work back to the state of production and then one would know that this same state is also relevant for the Λ^0 case. Of course, a determination of $\mathbf{p}_{\Sigma^0}$ amounts to a study of the polarization of the Λ^0 into which the Σ^0 rapidly decays. The secondary Λ^0 will have a polarization direction opposite to that of the parent Σ^0, but the degree of polarization is cut down by a factor one third. Furthermore, owing to kinematic effects, any dependence of $\mathbf{p}_{\Sigma^0}$ on the Σ^0 angle of emission would be reflected as a much weaker dependence of $\mathbf{p}_{\Lambda^0}$ on the Λ^0 angle. The use of the Σ^0 polarization to determine the initial orbital state does not therefore seem an easy task.

Of course, the present proposal hinges on the possibility of having available a source of polarized Σ^-'s, where the latter are to be brought to rest in hydrogen. In this connection it is relevant to remark that to date no significant up-down asymmetry has been observed in Σ^- decays, for Σ^- produced in (π^-,p) collisions.[1] This may be due to either or both circumstances that the Σ^- were not produced with appreciable polarization or that the intrinsic Σ^--decay mechanism does not generate appreciable up-down asymmetry. For our present purposes, the second possibility by itself is, of course, entirely irrelevant. Here we are only interested in the Λ^0 decay as a polarization analyzer and we do know this to function well. In fact, we may turn the argument around. The measurement of up-down asymmetry of Λ's produced in reaction (1) can be used to learn about the polarization of Σ^- produced from any source, independent of asymmetries in Σ^- decay. If the Λ's produced in (1) were to show appreciable asymmetry while the direct decay of the Σ^- coming from the same source showed very little, one would have independent information concerning the intrinsic Σ^- decay asymmetry. Information of this kind would, of course, be highly desirable in itself. There is some indication of up-down asymmetry in Σ decay for Σ's produced by K^- capture on nuclei.[9] At the time of writing the evidence does not seem conclusive. Clearly, however, Σ^- produced in this way—if polarized—would be useful for the purposes discussed here, since in general they are very slow and a reasonable fraction would come to rest and interact rather than decay.

Finally, we recall again that even if one can carry out experiments of the kind considered here, the results could be brought to bear on the question of the (Σ,Λ) parity only if one could determine, by independent means, the initial orbital state.

II. DETAILS

This section is devoted to a discussion of the coefficients a and b occurring in Eqs. (2) and (3) for the four types of pairings of initial and final orbital states. In each of these cases we deal with an aggregate of transitions that are further specified by initial and final spins and by total angular momentum. The situation is summarized in spectroscopic notation in Table I, where the column marked "amplitudes" presents the amplitude symbol assigned to each specific transition. We

[7] D. B. Lichtenberg and M. H. Ross, Phys. Rev. **107**, 1714 (1957).
[8] L. W. Alvarez *et al.*, Nuovo cimento **5**, 126 (1957).
[9] Quoted by F. S. Crawford *et al.*; see reference 1, footnote 1.

shall express $\mathbf{p}_\Lambda$ in general as follows:

$$R\mathbf{p}_\Lambda=\alpha\mathbf{p}_\Sigma+\beta(\mathbf{p}_\Sigma\cdot\mathbf{N})\mathbf{N}, \tag{5}$$

where R is the total rate of the reaction in question.

A. $S\rightarrow S$ Transitions

The transition operator T has the form, in the four-baryon spin space,

$$T=a_1X_t+a_2X_s,$$

where

$$X_t=\tfrac{1}{4}(3+\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2),\quad X_s=\tfrac{1}{4}(1-\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2)$$

are the triplet and singlet spin projection operators, respectively. That is to say, the transition matrix has the form

$$\tfrac{1}{4}(3a_1+a_2)(\Lambda,\Sigma)(n,p)+\tfrac{1}{4}(a_1-a_2)(\Lambda,\boldsymbol{\sigma}\Sigma)\cdot(n,\boldsymbol{\sigma}p),$$

where each particle symbol denotes the corresponding individual spin state. In terms of the parameters defined in Eq. (5) we get

$$\begin{aligned}R&=\tfrac{3}{4}|a_1|^2+\tfrac{1}{4}|a_2|^2,\\ \alpha&=\tfrac{1}{2}|a_1|^2+\tfrac{1}{2}\,\mathrm{Re}a_1{}^*a_2,\\ \beta&=0.\end{aligned} \tag{6}$$

Note that α contains a singlet-triplet interference term. This reflects our treatment of the initial triplet and singlet states as coherent.[10] This is certainly valid for transitions from the continuum. However, if the reaction takes place from the (lowest) singlet and triplet Bohr orbits we can have coherence only when the S-state reaction level width is comparable to or greater than the singlet-triplet separation. Expressed on a scale of time, this separation corresponds to $\sim 10^{-15}$ sec if the splitting is due to the hyperfine effect.[11] On the other hand, the very fact that the transition would take place from the bound S-states in question would mean that the $2P$-state reaction time for the process (1) is larger than the $2P$ to $1S$ radiative transition time. The latter time is $\sim 10^{-12}$ sec. Now it seems reasonable to suppose that the S-state reaction time is not shorter than the P-state time by three orders of magnitude. If this is indeed true, the triplet and singlet transitions are incoherent and it follows from Eqs. (5) and (6) that then

$$\mathbf{p}_\Lambda\leqslant\tfrac{2}{3}\mathbf{p}_\Sigma.$$

B. $S\rightarrow P$ Transitions

Define $\mathbf{S}$ and $\mathbf{S}'$ by

$$\mathbf{S}=\tfrac{1}{2}(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2),\quad \mathbf{S}'=\tfrac{1}{2}(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2).$$

In terms of these quantities the transition operator is now

$$T=(\tfrac{3}{2})^{\frac{1}{2}}b_1\mathbf{N}\cdot\mathbf{S}+\sqrt{3}b_2\mathbf{N}\cdot\mathbf{S}'X_t+b_3\mathbf{N}\cdot\mathbf{S}'X_s.$$

We then find

$$\begin{aligned}R&=\tfrac{3}{4}|b_1|^2+\tfrac{3}{4}|b_2|^2+\tfrac{1}{4}|b_3|^2,\\ \alpha&=-(\tfrac{3}{8})^{\frac{1}{2}}\,\mathrm{Re}b_1{}^*(\sqrt{3}b_2+b_3),\\ \beta&=\tfrac{3}{4}|b_1|^2+\mathrm{Re}[2^{\frac{1}{2}}b_1b_2{}^*+(\tfrac{2}{3})^{\frac{1}{2}}b_1b_3{}^*+(\tfrac{4}{3})^{\frac{1}{2}}b_2b_3{}^*].\end{aligned} \tag{7}$$

The (b_1,b_2) interference concerns two transitions taking place from the same initial state, so there can be no question here of incoherence. The (b_1,b_3) and (b_2,b_3) interference terms will, however, again vanish under the same circumstances discussed in the preceding paragraph. Observe also that if the ${}^3S\rightarrow{}^3P_1$ amplitude is preponderant, we get the simple expression

$$\mathbf{p}_\Lambda\approx(\mathbf{p}_\Sigma\cdot\mathbf{N})\mathbf{N},$$

which implies zero polarization for Λ's emitted perpendicular to the direction of initial Σ polarization.

C. $P\rightarrow S$ Transitions

The T operator is evidently similar in form to that for $S\rightarrow P$ transitions. The only essential difference is that the unit vector $\mathbf{N}$ is now to be replaced by a unit vector $\mathbf{n}$ in the direction of the relative Σ^--p momentum. One averages over directions of $\mathbf{n}$ in the final expressions. We obtain

$$\begin{aligned}R&=\tfrac{3}{4}|c_1|^2+\tfrac{3}{4}|c_2|^2+\tfrac{1}{4}|c_3|^2,\\ \alpha&=(12)^{-\frac{1}{2}}\{(\tfrac{3}{4})^{\frac{1}{2}}c_1{}^2-\mathrm{Re}[6^{\frac{1}{2}}c_1{}^*c_2+\sqrt{2}c_1{}^*c_3-c_2{}^*c_3]\},\\ \beta&=0.\end{aligned} \tag{8}$$

As we did for transitions from bound S states, we must discuss the question of coherence when the reaction takes place from a bound P state. Now if the reaction occurs from a bound $2P$ state, we know the reaction time is shorter than $\sim 10^{-12}$ sec. The periods corresponding to the expected $2P$ level splittings are of order 10^{-13} sec (the fine and hyperfine effects are about comparable here). If then the reaction time is larger

TABLE I. Summary of the $\Sigma^-\rightarrow\Lambda^0$ transitions.

(Σ,Λ) parity	Initial state	Final state	Amplitude
even	${}^3S_1$	${}^3S_1$	a_1
	${}^1S_0$	${}^1S_0$	a_2
	${}^3S_1$	${}^3P_1$	b_1
odd	${}^3S_1$	${}^1P_1$	b_2
	${}^1S_0$	${}^3P_0$	b_3
	${}^3P_1$	${}^3S_1$	c_1
odd	${}^1P_1$	${}^3S_1$	c_2
	${}^3P_0$	${}^1S_0$	c_3
	${}^3P_2$	${}^3P_2$	d_1
	${}^3P_1$	${}^3P_1$	d_2
even	${}^3P_1$	${}^1P_1$	d_3
	${}^1P_1$	${}^3P_1$	d_4
	${}^1P_1$	${}^1P_1$	d_5
	${}^3P_0$	${}^3P_0$	d_6

[10] We would like to thank Dr. J. Bernstein for a discussion of the coherence question.

[11] The Bohr radius in question is $\sim 10^{-11}$ cm. Thus spin-dependent (Σ^-,p) forces may distort the hyperfine separation, but probably not too much so.

than about 10^{-13} sec, we would have incoherence and all interference terms in Eq. (8) must be set equal to zero. In this situation we would have

$$\mathrm{p}_\Lambda \leqslant \tfrac{1}{3}\mathrm{p}_\Sigma.$$

D. $P \rightarrow P$ Transitions

The structure of the T operator in this rather complicated situation is as follows:

$$\begin{aligned} T = (\tfrac{3}{4})^{\frac{1}{2}}\{3d_1[4\mathbf{N}\cdot\mathbf{n}X_t - 3i\mathbf{S}\cdot(\mathbf{N}\times\mathbf{n}) - \mathbf{n}\cdot\mathbf{S}\mathbf{N}\cdot\mathbf{S}] \\ + d_2[i\mathbf{S}\cdot(\mathbf{N}\times\mathbf{n}) + \mathbf{n}\cdot\mathbf{S}\mathbf{N}\cdot\mathbf{S}] \\ + \sqrt{2}i\mathbf{S}'\cdot(\mathbf{N}\times\mathbf{n})(d_3X_t + d_4X_s) \\ + 2d_5\mathbf{N}\cdot\mathbf{n}X_s + \tfrac{2}{3}d_6[\mathbf{N}\cdot\mathbf{n}X_t - \mathbf{n}\cdot\mathbf{S}\mathbf{N}\cdot\mathbf{S}]\}. \end{aligned}$$

The symbols have previously been defined. At the end one averages over the directions of $\mathbf{n}$ (this is equivalent to averaging over the orbital magnetic quantum number in the initial P state). The final results are

$$\begin{aligned} R &= \tfrac{1}{12}\{5|d_1|^2 + 3(|d_2|^2 + |d_3|^2 + |d_4|^2 + |d_5|^2) + |d_6|^2\}, \\ \alpha &= \alpha_1 + \alpha_2, \\ \alpha_1 &= \tfrac{1}{8}(2|d_1|^2 - \sqrt{2}\,\mathrm{Re}\,d_2^*d_3), \\ \alpha_2 &= (1/24)\,\mathrm{Re}\{d_1^*(2d_2 + 3\sqrt{2}d_3 + 2\sqrt{2}d_4 + 6d_5) \\ &\qquad + d_2^*(3d_5 + 4d_6) + 2d_4^*(3d_3 - \sqrt{2}d_6)\}, \qquad (9) \\ \beta &= \beta_1 + \beta_2, \\ \beta_1 &= \tfrac{1}{8}(-|d_1|^2 + |d_2|^2 + \sqrt{2}\,\mathrm{Re}\,d_2^*d_3), \\ \beta_2 &= (1/24)\,\mathrm{Re}\{d_1^*(-d_2 + \sqrt{2}d_3 + 4\sqrt{2}d_4 + 2d_5) \\ &\qquad - d_2^*(6\sqrt{2}d_4 + 4d_6) - d_3^*(6d_4 + 4\sqrt{2}d_6) + 4d_5^*d_6)\}. \end{aligned}$$

The conditions for incoherence are the same as discussed in the previous paragraph. If they are met, then

$$\alpha_2 = \beta_2 = 0.$$

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Emission of Secondary Neutrons from Nuclei Bombarded by High-Energy Neutrons[*]

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The mean number of secondary neutrons emitted in a single act of absorption of 120- and 380-Mev neutrons by Be, C, Al, Fe, Cu, Sn, and Pb nuclei has been determined for secondary neutron energies up to ~15–20 Mev; the neutrons are predominantly emitted as a result of evaporation which occurs after an intranuclear nucleon cascade. The mean number of secondary neutrons was found to increase monotonically from carbon ($\nu = 1$–1.8) to lead ($\nu = 6.6$–9.9) and was almost constant when the primary neutron energy was varied from 120 to 380 Mev. The experimental results are compared with those obtained by studying star formation in nuclear emulsions and also fission of heavy nuclei and the production of neutrons by cosmic rays.

I. INTRODUCTION

DURING the years following the advent of the first relativistic heavy-particle accelerators a number of investigations were carried out on star formation induced by high-energy nucleons. Two stages of interaction between high-energy nucleons and nuclei were invoked to explain star formation, namely, an internal nucleon cascade in the nucleus and a subsequent process of evaporation of nucleons from the heated, excited nucleus.

Agreement between the theoretical predictions and experimental results pertaining to the main properties of cascade nucleons indicated that the intranuclear nucleon cascade model proposed by Goldberger[1] and developed by Bernardini[2] satisfactorily described the first stage of interaction between nuclei and high-energy nucleons. The second step of this interaction was theoretically studied in great detail by Le Couteur[3] on the basis of the particle evaporation concept proposed by Weisskopf.[4] It has been the object of a large number of investigations to check experimentally the theory of particle evaporation which is assumed to occur in the nuclear interaction of high-energy nucleons. However the results of these studies were not completely convincing since, as a rule, only nuclear emulsions or cloud chambers were employed.

Despite the merits of these methods they possess some serious shortcomings which become apparent when one uses them to study the dependence of star formation on mass number of the bombarding nuclei or, to an even greater extent, when they are employed in neutron emission studies. In general no systematic study of neutron emission in the interaction between

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