Phenomenological structure of the weak $\Lambda N \rightarrow NN$ interaction and the $\Delta I = \frac{1}{2}$ rule

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We study the implications of new data (from Brookhaven) on features of the weak nonmesonic decays of Λ hypernuclei and on our understanding of the $\Lambda N \rightarrow NN$ process. We follow the phenomenological analysis of Block and Dalitz; there is no need, however, to assume the validity of the $\Delta I = \frac{1}{2}$ rule. The importance of and need for higher-quality and newer data is demonstrated.

A free Λ hyperon decays weakly mostly into a nucleon and a pion via the weak nonleptonic decay

$$\Lambda \rightarrow p\pi^- \; (\sim 64\%)$$
$$\rightarrow n\pi^0 \; (\sim 36\%) , \qquad (1)$$

with an approximate lifetime $\tau_\Lambda \simeq 2.63\times 10^{-10}$ sec. The energy released in the free decay is about 37 MeV, and the corresponding c.m. momentum of the nucleon and pion is about 100 MeV/c.

Hypernuclei in their ground states (g.s.'s), when they are stable with respect to strong decay modes (particle emission), also decay via weak-interaction mechanisms. The situation described above for the weak decay of the free Λ hyperon changes dramatically when the Λ is embedded in the nuclear medium. The pionic weak-decay mode, Eq. (1), is strongly suppressed by phase-space and Pauli-blocking considerations, and a nonmesonic weak-decay mode is introduced.[1] Although the detailed microscopic mechanism for such decays is not understood at present, it is generally believed and/or assumed that a two-body interaction takes place (see Fig. 1):

$$\Lambda + p \rightarrow n + p , \qquad (2a)$$

$$\Lambda + n \rightarrow n + n . \qquad (2b)$$

This decay mode corresponds to an energy release of approximately 176 MeV, leaving each of the final nucleons with a momentum of about 417 MeV/c, and is therefore expected to dominate the weak-decay process in medium and heavy hypernuclei. Available experimental data do, indeed, support this expectation.[1] This nonmesonic, two-body decay mode resembles the weak nucleon-nucleon interaction — but with a large amount of additional new physics. The nonmesonic decays represent an interesting opportunity for the study of baryon-baryon weak interactions. In this process, both parity-conserving (PC) and parity-violating (PV) partial rates can be measured, whereas in the weak N-N case the strong interaction masks the PC signal of the weak interaction. (The strong interaction makes no contribution to the $\Lambda N \rightarrow NN$ interaction since strangeness is not conserved in this process.)

Detailed information on the nonmesonic decay modes would be a useful test of models of the weak interaction. Presently, there are no data on the free $\Lambda N \rightarrow NN$ reaction, and hypernuclear systems are the only source of information on this process. This complicates the study of the weak nonmesonic decays since, in addition to the reaction mechanism, one has to deal simultaneously with complicated hypernuclear structure effects. Block and Dalitz[2] showed that a number of important properties of the $\Lambda N \rightarrow NN$ amplitudes can be extracted from the existing data for light Λ-hypernuclear nonmesonic weak decays, without detailed knowledge of the microscopic interaction mechanism. The purpose of this work is to study the implications of recent data from Brookhaven[3] on the analysis of Block and Dalitz.[2] Interestingly, almost thirty years after the publication of the original work, this type of phenomenological analysis still seems to be the best way of studying the process, as no satisfactory microscopic understanding of the pertinent interaction has been attained so far.

As we shall see, the quality of the present data does not allow for firm conclusions to be drawn. Our subsequent discussion would result in interesting conjectures rather than conclusions. At the very least, this paper should serve two useful purposes: (i) it will demonstrate the need for and interest in new measurement (at Brookhaven and elsewhere); (ii) it will show that, despite our total lack of microscope understanding (e.g., in terms of meson exchanges) of the elementary $\Lambda N \rightarrow NN$ reaction,[1] it is still interesting and useful to study hypernuclear weak decays

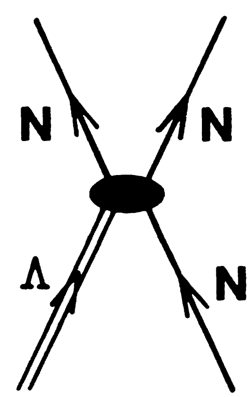

FIG. 1. The nonmesonic two-body weak-decay mode $\Lambda + N \rightarrow N + N$.

as tantalizing questions may be resolved using the methods discussed here.

The properties of interest of the $\Lambda N \to NN$ weak interaction are its isospin and spin dependence. As a result of the fairly low Λ-N relative momenta anticipated for light nuclei, only a relative two-body s state will be considered here (indeed, with a Λ hyperon and a nucleon both occupying a $1s$ harmonic-oscillator shell-model state, the relative Λ-N state is also an s wave). Under these conditions, the possible $\Lambda N \to NN$ transitions are listed in Table I, where R_{NJ} are the partial Λ-N capture rates for total angular momentum J, per unit nucleon density at the position of the Λ. Moreover,

$$R_{NJ} = \sum_{\beta} R(\alpha \to \beta) , \tag{3}$$

where the individual transition rates from an s-wave initial state α to a final state β are denoted by $R(\alpha \to \beta)$. The required partial rates for $\Lambda p \to np$ and $\Lambda n \to nn$ can be identified from Table I and then used in Eq. (3) to get R_{NJ} [e.g., $R_{p0} = R(^1s_0 \to {}^1s_0) + R(^1s_0 \to {}^3p_0)$]. Note that for $\Lambda N \to nn$ the final state has only isospin $I_f = 1$, so transitions are not possible to the states $^3s_1$, $^3d_1$, and $^1p_1$.

It is not known whether the $\Delta I = \frac{1}{2}$ rule is satisfied for the $\Lambda N \to NN$ interaction. Given its validity for other $|\Delta S| = 1$ transitions, Block and Dalitz[2] assumed that the $\Delta I = \frac{1}{2}$ rule holds for nonmesonic decays as well. Consequently, the neutron-induced partial decay rate is twice as large as the proton-induced one for the $I_f = 1$ transitions; this is true irrespective of the detailed decay mechanism (as long as the $\Delta I = \frac{1}{2}$ rule holds). As a consequence (see Table I),

$$\begin{aligned} R_{n0} &= 2R_{p0} , \\ R_{n1} &\le 2R_{p1} . \end{aligned} \tag{4}$$

One of the main objectives of the present work would be a possible test of the validity of the $\Delta I = \frac{1}{2}$ rule, relying on new data.

In the ensuing discussion we follow closely Ref. 2. The treatment is based on the assumption that the process of Λ deexcitation by different nucleons is incoherent. Such a procedure neglects final-state interactions for the two outgoing nucleons as well as interference effects resulting from antisymmetrization of the final NN state. These corrections are not expected to be important here because of the large energy release (some 170 MeV) and the high momentum (over 400 MeV/c each) of the outgoing nucleons; moreover, final states are summed over. A similar calculational scheme for the (strong) two-body conversion process $\Sigma N \to \Lambda N$ was developed and called "semiclassical" by Gal and Dover.[4,5] It has been derived on the basis of both the "$t\rho$" approximation (by constructing the first-order Σ optical potential)[4] and Fermi's "golden rule,"[5] based on an incoherent sum over the pertinent orbitals. Here, the assumption is justified by the relatively large energy and momentum transfers. Corrections to this scheme have been estimated to be small, and the procedure found to be reliable.[6]

The above remarks do not preclude a more detailed evaluation of the final-state interaction effects. It is possible that a detailed calculation would yield an unexpectedly large effect and render the extraction of the R_{NJ} amplitudes from the data much more complicated. Although we believe that this is a rather remote possibility, such a calculation should be encouraged. In the present work we are not concerned with such corrections since (a) the data are rather inaccurate, and, in our opinion, do not justify at present the calculation of relatively modest corrections; (b) based on the available data, the effects we find are rather large (albeit with large error bars) and no *qualitative* changes are expected to emerge from the final-state interactions.

Some authors[7] have considered the effects of distortion of the outgoing nucleons in the optical potential of the residual nucleus. The effect was found to be small (about 10% for ^{12}C). However, reactive content considerations indicate a preference of the plane-wave calculation. Since all final states are summed over, no flux is lost to undetected channels and there is no need for nucleon-nucleus distortion.

Treating the Λ decay by different nucleons as incoherent and assuming a local Λ-N interaction, the nonmesonic decay rate for hypernucleus $^A_\Lambda Z$ is given by $\Gamma_{NM}(^A_\Lambda Z) = \rho_A \bar{R}(^A_\Lambda Z)$; $\bar{R}$ is the spin-isospin average of the R_{NJ} for this hypernucleus, and

$$\rho_A = (A-1) \int u_\Lambda^2(\mathbf{r}) \rho_N(\mathbf{r}) d\mathbf{r}$$

is the mean nucleon density at the Λ position, with u_Λ being the Λ wave function (s state) and ρ_N the nucleon density. Dalitz and Rajasekharan[8] calculated ρ_A and found $\rho_5 = 0.038$ fm^{-3} (for $^5_\Lambda$He) and $\rho_4 = 0.019$ fm^{-3} (for $^4_\Lambda$He). For $A = 4,5$ Dalitz *et al.* wrote[2,8]

$$\begin{aligned} \Gamma_{\rm NM}(^5_\Lambda{\rm He}) &= \rho_5 \bar{R}(^5_\Lambda{\rm He}) \\ &= \tfrac{1}{8}\rho_5(3R_{p1} + R_{p0} + 3R_{n1} + R_{n0}) , \\ \Gamma_{\rm NM}(^4_\Lambda{\rm He}) &= \rho_4 \bar{R}(^4_\Lambda{\rm He}) = \tfrac{1}{6}\rho_4(3R_{p1} + R_{p0} + 2R_{n0}) , \\ \Gamma_{\rm NM}(^4_\Lambda{\rm H}) &= \rho_4 \bar{R}(^4_\Lambda{\rm H}) = \tfrac{1}{6}\rho_4(2R_{p0} + 3R_{n1} + R_{n0}) , \end{aligned} \tag{5}$$

(Note that in $^4_\Lambda$H, for example, only the singlet interaction is effective for $\Lambda p \to np$.) Furthermore, defining the ratio of proton- to neutron-induced nonmesonic partial rates, $\nu = \Gamma^p_{\rm NM}/\Gamma^n_{\rm NM}$, we find

TABLE I. The partial rates contributing to Λ-hypernuclear nonmesonic decays starting from an initial relative s state for the Λ-N pair.

Initial state	$^1s_0(L=0,J=0)$		$^3s_1(L=0,J=1)$			
Final state	$^1s_0$	$^3p_0$	$^3s_1$	$^1p_1$	$^3d_1$	$^3p_1$
I_f	1	1	0	0	0	1
$\Lambda p \to np$	$\leftarrow R_{p0} \to$		$\leftarrow$	R_{p1}		$\to$
$\Lambda n \to nn$	$\leftarrow R_{n0} \to$		0	0	0	R_{n1}

$$\nu({}^5_\Lambda\mathrm{He})=\frac{3R_{p1}+R_{p0}}{3R_{n1}+R_{n0}}\ ,$$

$$\nu({}^4_\Lambda\mathrm{He})=\frac{3R_{p1}+R_{p0}}{2R_{n0}}\ , \qquad (6)$$

$$\nu({}^4_\Lambda\mathrm{H})=\frac{2R_{p0}}{3R_{n1}+R_{n0}}\ .$$

On the basis of Eq. (5) and (6), and the data of $\nu({}^4_\Lambda\mathrm{He})=2.2\pm0.8$, $\Gamma_{\mathrm{NM}}({}^4_\Lambda\mathrm{He})=(0.157\pm0.03)\Gamma_\Lambda$, Block and Dalitz deduced directly that $R_{n0}=(7.4\pm2.4)\Gamma_\Lambda$ fm^3, and $\frac{1}{4}(3R_{p1}+R_{p0})=(8.2\pm2.0)\Gamma_\Lambda$ fm^3, without assuming the $\Delta I=\frac{1}{2}$ rule. Note that Block and Dalitz used a value of Γ_Λ which is higher by some 12% than the currently measured value of 3.80×10^9 sec^{-1}; their results have been roughly adjusted here to the more recent value.

In order to make further progress, the $\Delta I=\frac{1}{2}$ rule was used in Ref. 2. Thus, $R_{n0}=2R_{p0}$ gave $R_{p1}=(9.6\pm3.3)\Gamma_\Lambda$ fm^3, and the rate $\Gamma_{\mathrm{NM}}({}^4_\Lambda\mathrm{H})=(0.235^{+0.06}_{-0.07})\Gamma_\Lambda$ resulted in $R_{n1}=(19.2\pm6.7)\Gamma_\Lambda$ fm^3. From these results, we find that $R_{n1}/2R_{p1}=1\pm0.7$, $R_{p1}/R_{p0}=2.6\pm1.7$, and $R_{n1}/R_{n0}=2.6\pm1.7$. Although it was difficult to reach definite conclusions given the wide ranges quoted above, Block and Dalitz noted that the conceivable $R_{n1}\simeq 2R_{p1}$ implies the dominance of transitions to $I_f=1$ final states, while $R_{p1}\gg R_{p0}$ implies that the spin-triplet ($J=1$) channel dominates over the spin-singlet ($J=0$) state. If both conditions are valid, then the strongest $\Lambda N\to NN$ transition is the ${}^3s_1\to{}^3p_1$, and the next strongest are the ${}^1s_0\to{}^1s_0$, ${}^3p_0$, $I_f=1$ transitions. This result corresponds to the complete $\Lambda n\to nn$ amplitude, since the final nn state has only $I_f=1$. It has a great importance for constraining microscopic theoretical models of the microscopic $\Lambda N\to NN$ interaction. For example, the one-pion-exchange interaction strongly suppresses the parity-violating transitions and the $I_f=1$ states.

The conclusions of the preceding paragraph rely on the $\Delta I=\frac{1}{2}$ rule. From Eqs. (5) and (6) it is clear that a datum for ${}^5_\Lambda$He would make it possible to derive values of R_{NJ} independently of the $\Delta I=\frac{1}{2}$ rule. Indeed, such measurements have recently been attempted at Brookhaven,[3] yielding

$$\Gamma_{\mathrm{NM}}({}^5_\Lambda\mathrm{He})=(0.44^{+0.15}_{-0.31})\Gamma_\Lambda\ , \qquad (7)$$

as well as

$$\Gamma^p_{\mathrm{NM}}=(0.19\pm0.07)\Gamma_\Lambda\ , \qquad (8a)$$

$$\Gamma^n_{\mathrm{NM}}=(0.25^{+0.11}_{-0.30})\Gamma_\Lambda\ , \qquad (8b)$$

and

$$[\nu({}^5_\Lambda\mathrm{He})]^{-1}=1.30^{+0.65}_{-1.6}\ . \qquad (9)$$

Existing error bars on the experimental results are currently too large to allow for a definitive discussion; however, the following observations are of interest.

We start by using Eq. (7), in addition to the data used by Block and Dalitz, where

$$\tfrac{1}{4}(3R_{p1}+R_{p0})=(8.2\pm2.0)\Gamma\mathrm{fm}^3$$

was obtained. Thus, we find from the expression for $\Gamma_{\mathrm{NM}}({}^5_\Lambda\mathrm{He})$, Eq. (5), that

$$\tfrac{1}{4}(3R_{n1}+R_{n0})=(15^{+10}_{-15})\Gamma_\Lambda\mathrm{fm}^3$$

and

$$(3R_{n1}+R_{n0})/(3R_{p1}+R_{p0})=1.8^{+1.7}_{-1.8}\ .$$

Consequently, the ${}^4_\Lambda$H nonmesonic decay rate used in Ref. 2 and Eq. (5) yields $R_{p0}=(7^{+40}_{-7})\Gamma_\Lambda$ fm^3, and $R_{p1}/R_{p0}=1.3^{+9}_{-1.3}$. The latter numerical result is actually consistent with that of Block and Dalitz; indeed, strictly speaking the error bars are too large to allow any definite conclusion. However, examining just the central value, $R_{p1}/R_{p0}=1.3$, no longer implies a dominant spin-triplet channel in the $\Lambda N\to NN$ transition. Furthermore, using $R_{n0}=(7.4\pm2.4)\Gamma_\Lambda$ fm$_3$ from Block and Dalitz, we obtain the value $R_{n1}=(21^{+14}_{-21})\Gamma_\Lambda$ fm^3. This result for R_{n1} gives $R_{n1}/R_{n0}=2.8\pm2.8$. Taken at central value, this is in disagreement with the central value of R_{p1}/R_{p0}, implying different structures for the proton- and neutron-induced decay amplitudes, or perhaps indicating that other processes, different in nature from the two-body $\Lambda N\to NN$ mechanism, contribute appreciably. Moreover, we find that $R_{n0}/R_{p0}=1.1^{+6.0}_{-1.1}$. The central value $R_{n0}/R_{p0}=1.1$ implies a violation of the $\Delta I=\frac{1}{2}$ rule (the $\Delta I=\frac{1}{2}$ rule gives $R_{n0}/R_{p0}=2$). These will be our main conjectures here; we emphasize again that the pertinent error bars are very large.

The above error bars may be reduced somewhat by using Eqs. (8a) and (8b) for Γ^p_{NM} and Γ^n_{NM}. These give

$$\tfrac{1}{4}(3R_{p1}+R_{p0})=(10.0\pm3.7)\Gamma_\Lambda\ \mathrm{fm}^3$$

and

$$\tfrac{1}{4}(3R_{n1}+R_{n0})=(13.2^{+5.8}_{-13.2})\Gamma_\Lambda\ \mathrm{fm}^3\ ,$$

which are consistent with the values used by Block and Dalitz and in our analysis above. They yield, along similar lines, $R_{p1}/R_{p0}=0.69^{+2.26}_{-0.69}$, $R_{n1}/R_{n0}=2.7^{+2.0}_{-2.7}$, $R_{n1}/2R_{p1}=1.4^{+2.4}_{-1.4}$, and $R_{n0}/R_{p0}=0.69^{+1.58}_{-0.69}$. Using the central values, our above conjectures are reinforced, no dominance of the $I_f=1$ transition is established, and the $\Delta I=\frac{1}{2}$ rule seems to be strongly violated.

Similar conclusions, albeit with even larger error bars, can be drawn from the ratio $\nu({}^5_\Lambda\mathrm{He})$, Eq. (9). Since we have already demonstrated the large error bars on our results, we shall contentedly give here only the central values. We find from Eq. (6) that

$$3R_{n1}+R_{n0}=1.3(3R_{p1}+R_{p0})\ ;$$

the numerical value of

$$\tfrac{1}{4}(3R_{p1}+R_{p0})=(8.2\pm2.0)\Gamma_\Lambda\ \mathrm{fm}^3\ ,$$

from Block and Dalitz, yields the central value

$$\tfrac{1}{4}(3R_{n1}+R_{n0})=10.7\Gamma_\Lambda\ \mathrm{fm}^3\ ,$$

which is consistent with our previous analysis. [We can also use Eqs. (9) *and* (7) together, to obtain the ratio *and* the sum of $\frac{1}{4}(3R_{n1}+R_{n0})$ and $\frac{1}{4}(3R_{p1}+R_{p0})$. This gives

TABLE II. Results and conclusions concerning the $\Lambda N \rightarrow NN$ weak interaction.

	Result	Conclusions	Comment
Block and Dalitz	$R_{n0}/R_{p0}=2$	$\Delta I=\frac{1}{2}$ rule	Input
	$R_{n1}/R_{p1}=2$	Dominance of transitions to $I_f=1$ states	
	$R_{p1}/R_{p0}=2.6$ $R_{n1}/R_{n0}=2.6$	Dominance of the spin-triplet channel	
This work, Eq. (7)	$R_{p1}/R_{p0}=1.3$	No dominance of a particular spin channel	Validity of the $\Delta I=\frac{1}{2}$ rule not assumed in this work
	$R_{n1}/R_{n0}=2.8$	See text	
	$R_{n0}/R_{p0}=1.1$	$\Delta I=\frac{1}{2}$ rule violated	
This work, Eqs. (8a),(8b)	$R_{p1}/R_{p0}=0.69$ $R_{n1}/R_{n0}=2.7$ $R_{n0}/R_{p0}=0.69$	Above conclusions reinforced	
This work, Eq. (9)	$R_{p1}/R_{p0}=0.36$ $R_{n1}/R_{n0}=1.6$ $R_{n0}/R_{p0}=0.47$		

$\frac{1}{4}(3R_{p1}+R_{p0})=8.9\Gamma_\Lambda$ fm^3, consistent with the result obtained by Block and Daltiz. However, our result for $\frac{1}{4}(3R_{n1}+R_{n0})$ is substantially different from that of Block and Dalitz, when only the central values are considered.] Using the Block-Dalitz $R_{n0}=7.4\Gamma_\Lambda$ fm^3, we find $R_{n1}/R_{n0}=1.6$, very different from our first results, namely, ~ 2.8. Next, with $\Gamma_{NM}(^4_\Lambda H)$ we find $R_{p1}/R_{p0}=0.36$, i.e., if $\Lambda N \rightarrow NN$ is the dominant decay process it would have a large spin-singlet, $J=0$ component, in contrast with Block and Dalitz. Finally, $R_{n0}/R_{p0}=0.47$ implying a major violation of the $\Delta I=\frac{1}{2}$ rule in the $\Lambda N \rightarrow NN$ weak interaction (recall that by the $\Delta I=\frac{1}{2}$ rule, $R_{n0}/R_{p0}=2$).

Although these results are intriguing, we emphasize again that the large pertinent error bars do not allow for any definite conclusions to be drawn at this time. However, given the possibility that some of our conjectures may be valid, more precise experimental measurements are evidently called for and eagerly awaited. Moreover, the lack of theoretical understanding of the elementary $\Lambda N \rightarrow NN$ interaction (e.g., in terms of meson exchanges) does not have severe implications for the work presented here, and this type of phenomenological analysis is useful and meaningful.

In conclusion, we present in Table II the main results and conclusions reached in this work *based on central values only.*

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