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POSSIBLE VIOLATION OF THE ΔI=1/2 RULE IN NON-MESONIC HYPERNUCLEAR WEAK DECAY

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ABSTRACT

The weak decays of strange mesons and free hyperons strongly favor ΔI=1/2 amplitudes over ΔI=3/2 amplitudes. It is not known to what extent this rule applies to the non-mesonic interactions of the type $\Lambda p \rightarrow np$ and $\Lambda n \rightarrow nn$. This paper examines existing data on non-mesonic decays of light hypernuclei in order to obtain a quantitative estimate of the relative strength of the two isospin channels. The data show that a pure ΔI=1/2 decay amplitude is ruled out at the 1.6σ level, and favor a solution where either: 1) both isospin channels contribute about equally, or 2) the ΔI=3/2 channel dominates by an order of magnitude.

1. INTRODUCTION

An unresolved question which has endured for many years is why strangeness changing weak interactions prefer the ΔI = 1/2 channel over the *a priori* comparably strong ΔI = 3/2 channel. This effect can be large, about a factor of 20 in mesonic K decay amplitudes, and is also seen in the mesonic decays of hyperons. However, little experimental information exists to test the ΔI=1/2 rule in the strangeness changing weak interaction between two baryons, such as a Λ and a nucleon. There are few ways to observe this non-mesonic interaction; in particular, hyperon-nucleon scattering is experimentally difficult and no one has looked for weak interaction effects. The only practical way to study the strangeness changing YN interaction is to examine the non-mesonic decays of hyperons embedded in nuclei. In the mesonic decays, where the ΔI = 1/2 rule is known to work well, the typical center-of-mass momenta are 100 MeV/c, while in non-mesonic decays the typical momenta are about 400 MeV/c. Cohen [1] has pointed out that in one-pion exchange models the non-mesonic decays probe the parity conserving, higher momentum p-wave part of the weak interaction, which is masked by the strong interaction in non-strange NN interactions. All current models of non-mesonic decays make the assumption that the ΔI = 1/2 rule is valid, and have achieved reasonable agreement with data on the total non-mesonic decay rates. However, no model has succeeded in reproducing the measured ratios of Λn→nn and Λp→np widths. It is interesting, therefore, to further test the validity of the isospin rule for the less well understood, high momentum, parity conserving part of the interaction. We examine here the existing data for non-mesonic decays of helium and hydrogen hypernuclei and find evidence of a violation of the usual ΔI = 1/2 rule.

2. THEORETICAL MODEL

The non-mesonic decay rates for $\Lambda + p \rightarrow n + p$ (partial rate Γ_p) and $\Lambda + n \rightarrow n + n$ (partial rate Γ_n) are sensitive to the spin-isospin structure of the strangeness changing weak interaction in nuclei (For a recent review see Ref 1]). Figure 1 illustrates the paths by which a ΛN initial spin configuration with isospin 1/2 can decay non-mesonically to an NN final state spin and isospin configuration. The $\Lambda n \rightarrow nn$ transition is forbidden by the Pauli principle for I=0 final states. Note that comparison of data from several light hypernuclei, such as ${}^{5}_{\Lambda}He$ and ${}^{4}_{\Lambda}He$, provides a filter for isolating contributions from specific spin channels. An example of a theoretical prediction is shown in the figure: in lowest-order calculations involving one-pion exchange only, the ${}^{3}S_{1} \rightarrow {}^{3}D_{1}$ transition dominates. The effects of initial state correlations and the inclusion of ρ, K, and other meson exchanges redistribute the decay strength to other spin channels, as shown for the case of a calculation by Dubach [2].

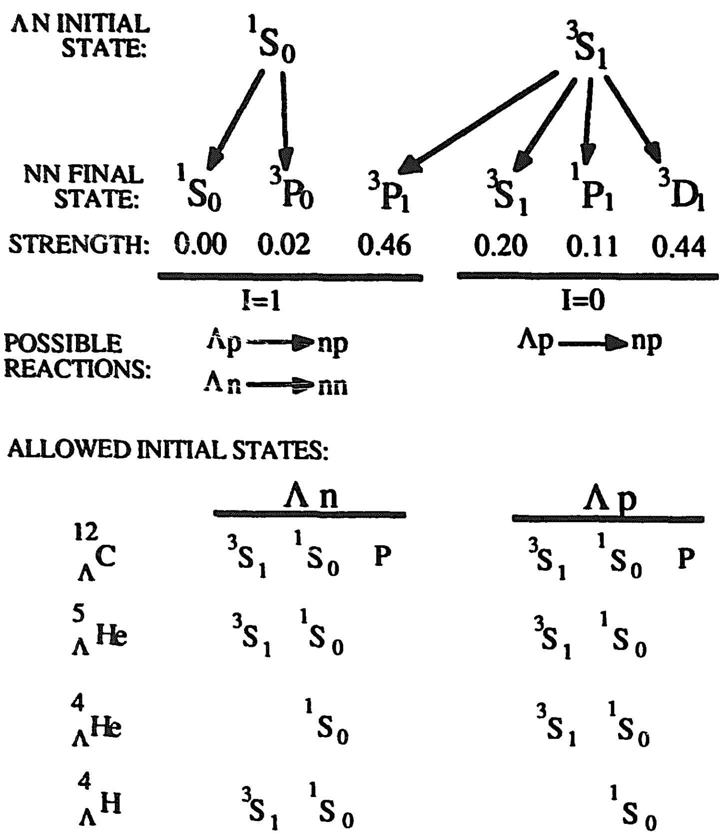

Figure 1. Spin and isospin combinations for non-mesonic weak decay of light hypernuclei. The predicted strengths for the separate channels are from Ref 2].

The neutron- and proton- stimulated partial decay rates to the three I=1 final states can be related as follows. We designate the neutron stimulated decay rate to an I=1 final state via any spin channel by R_n, and the corresponding proton stimulated decay rate by R_p. Any weak decay operator, O, may be divided into parts $O_{1/2}$ and $O_{3/2}$ which have isospin 1/2 and 3/2, respectively. Then we can write:

$$R_n \propto \left| \langle I_f=1; I_{fz}=-1 | O_{3/2} | I_i=\tfrac{1}{2}; I_{iz}=-\tfrac{1}{2} \rangle + \langle I_f=1; I_{fz}=-1 | O_{1/2} | I_i=\tfrac{1}{2}; I_{iz}=-\tfrac{1}{2} \rangle \right|^2$$

and (1)

$$R_p \propto \left| \langle I_f=1; I_{fz}=0 | O_{3/2} | I_i=\tfrac{1}{2}; I_{iz}=+\tfrac{1}{2} \rangle + \langle I_f=1; I_{fz}=0 | O_{1/2} | I_i=\tfrac{1}{2}; I_{iz}=+\tfrac{1}{2} \rangle \right|^2$$

Using the Wigner-Eckart theorem to eliminate the I_z dependence of these expressions, we find that

$$R_n \propto \left|\frac{1}{\sqrt{12}}\langle 1 \| O_{3/2} \| \tfrac{1}{2}\rangle - \frac{1}{\sqrt{3}}\langle 1 \| O_{1/2} \| \tfrac{1}{2}\rangle\right|^2$$

and (2)

$$R_p \propto \left|-\frac{1}{\sqrt{6}}\langle 1 \| O_{3/2} \| \tfrac{1}{2}\rangle - \frac{1}{\sqrt{6}}\langle 1 \| O_{1/2} \| \tfrac{1}{2}\rangle\right|^2$$

If the $\langle O_{1/2}\rangle$ amplitude dominates the reaction mechanism we see that the ratio of partial rates R_n/R_p is expected to be 2, while if the $\langle O_{3/2}\rangle$ amplitude were to dominate we would find $R_n/R_p = 1/2$. In general, if both amplitudes contribute and their relative strength is defined as

$$\lambda \equiv \frac{\langle 1 \| O_{3/2} \| \tfrac{1}{2}\rangle}{\langle 1 \| O_{1/2} \| \tfrac{1}{2}\rangle}, \tag{3}$$

then the experimental determination of R_n/R_p determines λ up to a quadratic ambiguity:

$$R_n/R_p = \frac{\lambda^2 + 4 - 4\lambda}{2\lambda^2 + 2 + 4\lambda}. \tag{4}$$

It has been assumed that the two reduced matrix elements are relatively real, as required by time reversal invariance [3].

Connection with experiment may be made by isolating the $^1S_0$ part of the ΛN decay mechanism because it leads only to the isospin 1 final states to which the above discussion applies. In the approach introduced by Block and Dalitz [4], and recently updated by Dover [5], one defines R_{NS} as the rate for $\Lambda N \rightarrow NN$ from spin state S. It follows from the above discussion that for pure $\Delta I=1/2$ decays we have $R_{n0} = 2R_{p0}$ (I=1 final state only) and $R_{n1} \leq 2R_{p1}$ (both I=0 and 1 final states). Hence the quantity which we want to extract from data is the ratio $r \equiv R_{n0}/R_{p0}$, which for pure $\Delta I=1/2$ decays must be 2.

The total non-mesonic decay rate for $^4_\Lambda He$ is written as an initial state spin and nucleon average of the rates R_{NS}:

$$\Gamma_{n.m.}(^4_\Lambda He) = \Gamma_n + \Gamma_p = \rho_4 \frac{1}{6}(3R_{p1} + R_{p0} + 2R_{n0}), \tag{5}$$

where the factor ρ_4 denotes the mean nucleon density at the Λ position. Similar expressions hold for $^5_\Lambda He$ and $^4_\Lambda H$, the other hypernuclei for which relevant data exist. Experiments have provided three moderately well measured ratios of non-mesonic decay rates, and these are:

$$\gamma_4 \equiv \frac{\Gamma_n}{\Gamma_p}(^4_\Lambda He) = \frac{2R_{n0}}{3R_{p1}+R_{p0}} = 0.40 \pm 0.15, \tag{6}$$

$$\gamma_5 \equiv \frac{\Gamma_n}{\Gamma_p}(^5_\Lambda He) = \frac{3R_{n1}+R_{n0}}{3R_{p1}+R_{p0}} = 0.93 \pm 0.55, \tag{7}$$

and

$$\gamma \equiv \frac{\Gamma_{n.m.}(^4_\Lambda He)}{\Gamma_{n.m.}(^4_\Lambda H)} = \frac{3R_{p1}+R_{p0}+2R_{n0}}{3R_{n1}+R_{n0}+2R_{p0}} = 0.53 \pm 0.22\,. \tag{8}$$

The numerical values come primarily from Refs. 4] and 6], though several additional data sets were examined in arriving at these "best" values, as discussed in the next section. Solving the three equations one obtains the ratio:

$$r \equiv \frac{R_{n0}}{R_{p0}} = \frac{\gamma\gamma_4}{1+\gamma_4-\gamma\gamma_5} = 0.23 \pm 0.17 \qquad (9)$$

This ratio tests the $\Delta I=1/2$ Rule, which predicts a value of 2, suggesting a rather large violation in the case of light hypernuclei. Caveats about the uncertainty on this quantity are discussed below.

This model makes several assumptions: 1) that the decay of the Λ as incoherent on all available nucleons; 2) that final state interactions of the nucleons have been corrected in the data; 3) that isospin breaking effects are negligible, as for example in Eq (6) where the proton and neutron do not enter symmetrically; 4) that the model parameter ρ_4 is the same for ^{4}He and ^{4}H; and 5) that decays to the $^1S_0$ and $^3P_0$ states have the same isospin structure. At the present level of accuracy, these assumptions are believed to be satisfied.

3. EXAMINATION OF THE DATA

The experimental values of γ_4, γ_5, and γ quoted above result from examination of all the available data, which are summarized in Table 1. The ratios of the non-mesonic rates, γ_4 and γ_5, have each been measured directly once. For γ there is one direct measurement, and an essentially independent though indirect way of calculating it from the other components of the total hypernuclear decay width and the lifetimes of the hypernuclei. This method uses the relation

$$\Gamma_{Total} = 1/\tau = \Gamma_{\pi^-} + \Gamma_{\pi^0} + \Gamma_{n.m.}, \qquad (10)$$

where Γ_{π^-}, Γ_{π^0}, and $\Gamma_{n.m.}$ are the charged and neutral pion partial decay rates and the total non-mesonic decay rate, respectively, and τ is the hypernuclear lifetime. Using the commonly-used definitions $Q^- = \Gamma_{n.m.}/\Gamma_{\pi^-}$ and $R_o = \Gamma_{\pi^0}/\Gamma_{\pi^-}$ one can easily show that

$$\gamma = \frac{\tau_H}{\tau_{He}} \frac{Q^-_{He}}{Q^-_H} \frac{(1+R_o+Q^-)_H}{(1+R_o+Q^-)_{He}}. \qquad (11)$$

The lifetime of $^4_\Lambda$He, denoted τ_{He}, was measured once in an emulsion experiment, [9] as quoted in Table 1. The systematic uncertainty of that number was large because of ambiguity in separating $^4_\Lambda$He and $^5_\Lambda$He hyperfragment events. The recent measurement [6] of the lifetime of $^5_\Lambda$He has lifted that ambiguity to a large extent and allows us to re-examine the old data to obtain a much smaller uncertainty for τ_{He}, as given in Table 1. This procedure leads to a value for γ using Eq.(11) which is in agreement with the direct measurement. We note that a new experiment at Brookhaven[12] has taken data which will provide improved values for γ_4 and γ_5.

4. DISCUSSION OF RESULTS

The significance of the ratio in Eq (9), which tests the $\Delta I=1/2$ rule, hinges on the associated experimental error. Treating the three ratios as independent and uncorrelated, we can combine the experimental errors as usual according to:

$$\sigma_r^2 = \sum_{i=1}^{3} \left(\frac{\partial r}{\partial \gamma_i}\right)^2 \sigma_i^2.$$

This leads to the error estimate $\sigma_r=0.17$, so that $r \equiv R_{n0}/R_{p0} = 0.22 \pm 0.17$. When compared to the pure $\Delta I=1/2$ expectation of $r = 2.0$ and the pure $\Delta I=3/2$ expectation of $r = 0.5$ there appears to be a large discrepancy. However, looking at the parameter correlations one finds that the uncertainty on r depends strongly on the correlated error between γ and γ_5. As a better uncertainty estimate we ask how likely it is that the present data are compatible with the $\Delta I=1/2$ rule. Assuming that r = 2, as predicted by the $\Delta I=1/2$ rule, we consider the space of values for $\{\gamma',\gamma_4',\gamma_5'\}$ which are consistent with that hypothesis. We find the *one* set of values from this space which is closest to the experimentally measured values by minimizing

$$\chi^2 = \sum_{i=1}^{3} \frac{1}{\sigma_i^2}(\gamma_i'-\gamma_i)^2 .$$

The result is a χ^2 for one degree of freedom of 2.7 (a 1.6σ deviation), which corresponds to a 10% probability that the r=2 hypothesis is correct, or a 90% probability that the data result from an r ratio other than 2. The values closest to the data, and the distance from the measured values in units of the measurement uncertainties are:

$$\begin{aligned} \gamma_4' &= 0.36 & -0.25\,\sigma_{\gamma 4} \\ \gamma_5' &= 1.59 & +1.19\,\sigma_{\gamma 5} \\ \gamma' &= 0.77 & +1.10\,\sigma_{\gamma} \end{aligned} \tag{12}$$

Taking the present experimental uncertainties as truly representing the total (statistical and systematic) errors on the data, the pure $\Delta I=1/2$ hypothesis is excluded at about the $1.6\,\sigma$ or 90% confidence level. Clearly it would be useful to have more measurements of these quantities to check this result.

Figure 2 shows the relationship between the measured ratio $r = R_{n0}/R_{p0}$ and the ratio of isospin 3/2 and 1/2 amplitudes, λ, as given by Eq (4). Both roots of λ are shown, where the sections of the curves to the right of the divergences correspond to a relative phase of π between amplitudes. The data prefer a value r=0.22 over r=2.0, which corresponds to a ratio of the $\Delta I=3/2$ to $\Delta I=1/2$ decay amplitudes, λ, of either $0.8\pm^{.5}_{.2}$ or $8\pm^{22}_{5}$, depending on which root is selected. The data offer no way to resolve this two-fold ambiguity. The uncertainty estimates for λ correspond to the uncorrelated error $\sigma_r=0.17$ and are therefore also to be considered lower limits on the actual uncertainty.

In view of the failure of present theoretical models to adequately explain the experimental ratios of non-mesonic weak decays, the present phenomenological analysis suggests that the failure may lie in the *a priori* invocation of the $\Delta I = 1/2$ rule in the decay mechanism in a case where it may not apply. The fact that these decays probe center-of-mass momenta not reached by mesonic decays, and that in one-pion exchange models they occur via the parity conserving part of the weak amplitude, it is plausible that non-mesonic decays may have a different isospin structure than the mesonic decays. This paper has examined the status of the existing experimental data, and made a quantitative estimate of how much the usual $\Delta I=1/2$ rule is violated by non-mesonic weak decays of Λ hypernuclei. In a phenomenological model, the data are not consistent with pure $\Delta I=1/2$ at the 1.6σ level, and suggests that the $\Delta I=3/2$ amplitude may be comparable to or possibly larger than the $\Delta I=1/2$ piece.

1) Joseph Cohen, Progress in Particle and Nuclear Physics **25** (1990) 139.
2) John F. Dubach, Nuclear Physics **A450** (1986) 71c.
3) R.Sorensen, private communication; A.Bohr & B.Mottelson, Nuclear Structure ,V.I, p. 96.
4) M.M. Block and R.H. Dalitz, Phys. Rev. Lett. **11** (1963) 96.
5) Carl B. Dover, Few-Body Systems, Suppl. **2** (1987) 77.
6) J.J.Szymanski *et al.*, Phys. Rev. C **43** (1991) 849.
7) M.M. Block *et al*, Nuovo Cimento, **28** (1963) 299.
8) Average of seven measurements listed in Ref. 1], plus H. Outa *et al*, these Proceedings.
9) R.E. Phillips and J. Schneps, Phys. Rev. **180** (1969) 1307.
10) Average of measurements from Ref 7] and J. McKenzie, cited in Ref. 1].
11) The value was taken from Ref. 7], not the discrepant tabulation in Ref. 1].
12) Brookhaven Experiment E788, G. Franklin and P.D.Barnes, spokesmen.

Table 1
Hypernuclear weak decay data used in this paper, revised as discussed in the text.

Measured Quantity	Value	Comments	Reference
γ_4	0.40 ±.15	^{4}He bubble chamber	7
γ_5	0.93 ±.55	spectrometer / counters	6
γ	0.48 ±.25	hyperfragments; direct meas.	4,7
	0.67 ±.44	indirect calculation; see text	
	0.53 ±.22	average of previous two	
$\tau({}^4_\Lambda H)$	194 ±30 psec	average	8
$\tau({}^4_\Lambda He)$	$228\,{}^{+233}_{-129}$ psec	as originally published	9
	$228\,{}^{+113}_{-67}$	revised; see text	
$Q^-({}^4_\Lambda He)$	0.56 ±.09	average	10
$Q^-({}^4_\Lambda H)$	0.26 ±.13	only measurement	7
$R_0({}^4_\Lambda He)$	2.20 ±.34	only measurement	7, 11

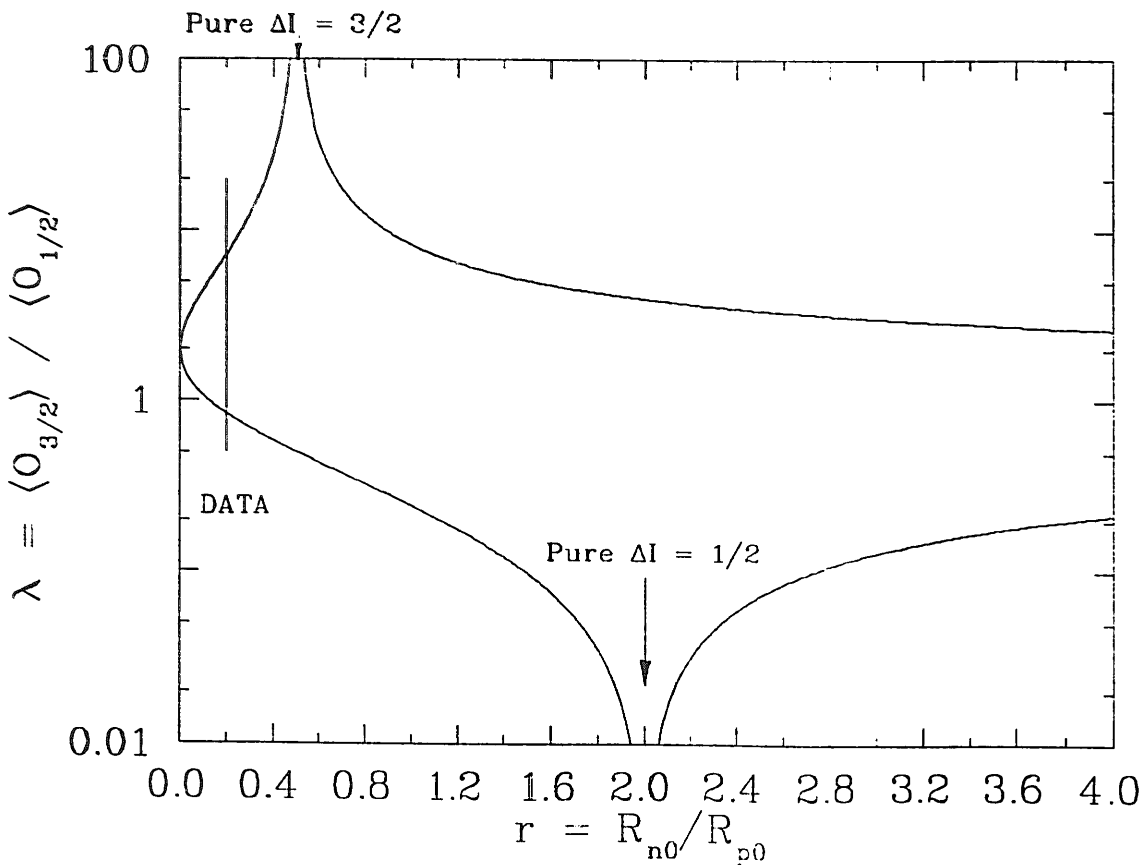

Figure 2. Ratio of the strangeness-changing weak decay amplitudes for ΔI=3/2 and ΔI=1/2 as a function of the measured ratio of neutron to proton stimulated decays from spin singlet initial ΛN configurations which lead to isospin 1 final states.