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PHYSICAL REVIEW D VOLUME 9, NUMBER 1 1 JANUARY 1974

Test of Cabibbo's model in hyperon semileptonic decays

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The experimental rates and angular correlation and symmetry coefficients are used to test Cabibbo's model in semileptonic hyperon decays. The data indicate that the one-angle model should be relaxed. We consider the possibility that $\theta_V \neq \theta_A$, and we investigate the influence of the q^2 dependence of the form factors. We find that the present data are sufficiently accurate to detect symmetry-breaking effects.

I. INTRODUCTION

The experimental evidence in hyperon semileptonic decays has increased lately, so that one can expect to have a better test of Cabibbo's model.[1] Previous recent tests[2–4] seem to favor the one-angle Cabibbo's model. Our present analysis aims at performing a more detailed test of this model and at investigating whether the current experimental evidence makes it worthwhile to consider symmetry-breaking corrections in semileptonic hyperon decays.

Instead of the experimental V/A ratios of the different decays, which have been used in the other tests, we prefer to use the available experimental angular correlation and asymmetry coefficients, because, otherwise, one would be losing information. In our opinion, this provides a more stringent test of the model.

In Sec. II, we review the parametrization in Cabibbo's model of the different hyperon semileptonic decays. In Sec. III, we use these parameters to fit the available data in this type of decays and we consider also the possibility that there be different vector and axial-vector Cabibbo angles. In Sec. IV we make some final comments.

II. PARAMETERS IN CABIBBO'S MODEL

We assume that the semileptonic decays of hyperons are all described by the $V-A$ theory, with time-reversal invariance, and electron-muon universality. For the internal-symmetry properties of these decays we take Cabibbo's model.[5] In the spirit of this model symmetry-breaking effects are assumed to be small enough to be neglected, except for the difference in the masses of the different hyperons. Also, only first-class currents are assumed.[6] The hadronic part of the transition amplitude is

$$\langle A|J_\mu|B\rangle = \left(\frac{M_A M_B}{E_A E_B}\right)^{1/2} \bar{u}_A(p')\Big\{ f_1(q^2)\gamma_\mu + f_2(q^2)\frac{\sigma_{\mu\nu}}{M_B}q_\nu + f_3(q^2)\frac{q_\mu}{M_B} + \left[g_1(q^2)\gamma_\mu + g_2(q^2)\frac{\sigma_{\mu\nu}}{M_B}q_\nu + g_3(q^2)\frac{q_\mu}{M_B}\right]\gamma_5\Big\} u_B(p), \tag{1}$$

where B and A are the decaying and decay baryons, $J_\mu = V_\mu - A_\mu$, $q = p - p'$, and M_B is the mass of baryon B. According to Cabibbo's model, the form factors g_2 and f_3 can only contribute as symmetry-breaking effects. These effects are assumed to be small enough so that the contribution of these form factors can be neglected. For the electron-mode decays, the contribution of g_3 will be multiplied by the electron mass. Therefore it can be ignored, unless g_3 turned out to be unreasonably large. Since the range of variation for q^2 is small in all of these decays, the q^2 dependence of the form factors that contribute can be accounted for by keeping the linear term in a q^2 expansion,[7] say,

$$f_i^{AB}(q^2)=f_i^{AB}(0)\left(1+\lambda_i^{AB}\frac{q^2}{M_B{}^2}\right), \tag{2}$$

where $i=1,2,3,4$; $f_3^{AB}(q^2)\equiv g_1^{AB}(q^2)$ and $f_4(q^2)\equiv g_3^{AB}(q^2)$. Cabibbo's model gives the form factors as

$$f_i^{AB}(0)=(f_{ABC}F_i+d_{ABC}D_i)\,T_i(\theta_V), \tag{3}$$

where F_i and D_i are reduced form factors, $T(\theta_V)$ is $\cos\theta_V$ for $\Delta S=0$ decays or $\sin\theta_V$ for $|\Delta S|=1$ decays, and f_{ABC} and d_{ABC} are Clebsch-Gordan coefficients. The vector-form-factor reduced matrix elements as well as the slopes $\lambda_{1,2}^{AB}$ can be determined from the conserved-vector-current hypothesis. See, for example, Refs. 5 and 7. The reduced axial-vector form factors F_3 and D_3, which we call simply F and D, as well as their slopes, remain undetermined. We think it is acceptable to suppose a common slope for F and D, since the experimental data are insensitive to any small difference there could be between their slopes. Then, the slopes of the different axial-vector form factors $g_1^{AB}(q^2)$ can all be put in terms of a single slope parameter, which we call λ. If one uses axial-vector-meson dominance, λ can be estimated to be about unity,[7] or else it can be left free to fit the data. In the muon-mode decays, the induced pseudoscalar form factors g_3^{AB} may contribute because the muon mass is not negligible. They can be related to the g_1^{AB}, via partially conserved axial-vector current (PCAC). For this, we use PCAC as in Ref. 8. Finally, there remain three parameters to fit the data (namely, F, D, and θ_V), or four if λ is left free.

III. COMPARISON WITH THE DATA

We have tested the one-angle Cabibbo model by performing a χ^2 fit to the experimental numbers displayed in Table I.[9-13] We have used as free parameters F, D, and θ_V, keeping λ fixed at its axial-vector-meson-dominance value. The theoretical expressions for the rates were taken from Refs. 7 and 14, and the expressions for the different angular coefficients were taken from Ref. 15. The values of the parameters for this fit are

$$\begin{aligned} F&=0.466\pm0.009\,,\\ D&=0.809\pm0.009\,,\\ \theta_V&=0.236\pm0.004 \end{aligned} \tag{4}$$

at a confidence level (C.L.) of 1.3% ($\chi^2_{\min}=28.56$) for 14 degrees of freedom. The predicted values for the different quantities are displayed in the third column of Table I. We have estimated the error bars as those which represent one standard deviation along each coordinate from the $\chi^2{}_{\min}$ point. The fit is poor. The main causes of trouble are the electron asymmetry in $\Sigma^-\to ne\bar\nu$, which is off its experimental counterpart by more than two standard deviations, and the neutrino asymmetry in $\Lambda\to pe\bar\nu$, which is virtually at the three-standard-deviation limit. In addition there are five quantities off by somewhat more than one standard deviation. See also Ref. 16. Allowing the slope parameter λ to be free leads to the result $\lambda=-1.28\pm0.66$ at a C.L. of 9% ($\chi^2_{\min}=20.32$) for 13 degrees of freedom. The values of F, D, and θ_V remain almost equal. Although the fit is improved somewhat, λ is fixed at a negative value quite far from its axial-vector-meson-dominance estimate. This seems rather hard to understand even if axial-vector-meson dominance were only very roughly correct. We think these results show that the one-angle Cabibbo model must be relaxed.

It is possible that there are two different Cabibbo angles, one for the vector current θ_V and another one for the axial-vector current θ_A. We have tried this possibility. That is, we have tested the so-called parallelism hypothesis in Ref. 17. In this case the free parameters are F, D, θ_V,

TABLE I. Experimental rates and angular coefficients and corresponding predicted values for the one- and two-angle fits. The first nine rows give transition rates in $10^6\ \mathrm{sec}^{-1}$, except $n\to pe\bar\nu$, which is in $10^{-3}\ \mathrm{sec}^{-1}$. λ is the slope parameter.

Decay	Experiment	One-angle	Two-angle
$n\to pe\bar\nu$	1.070 ± 0.016 [a]	1.050	1.054
$\Lambda\to pe\bar\nu$	3.353 ± 0.139 [a]	3.401	3.404
$\Sigma^+\to\Lambda e\nu$	0.252 ± 0.059 [a]	0.277	0.249
$\Sigma^-\to\Lambda e\bar\nu$	0.407 ± 0.040 [a]	0.459	0.414
$\Sigma^-\to ne\bar\nu$	7.385 ± 0.325 [a]	7.075	7.032
$\Xi^-\to\Lambda e\bar\nu$	6.928 ± 5.404 [a]	3.050	3.673
$\Lambda\to p\mu\bar\nu$	0.643 ± 0.138 [a]	0.562	0.564
$\Sigma^-\to n\mu\bar\nu$	3.012 ± 0.289 [a]	3.303	3.309
$\left.\begin{matrix}\Xi^-\to\Lambda e\bar\nu\\ \Xi^-\to\Sigma e\bar\nu\end{matrix}\right\}$	$3.735^{+1.206}_{-1.808}$ [a]	3.595	4.152
$np\ \alpha_{e\nu}$	-0.095 ± 0.028 [b]	-0.107	-0.110
$np\ \alpha_e$	-0.114 ± 0.007 [b]	-0.119	-0.124
$np\ \alpha_\nu$	1.001 ± 0.038 [b]	0.987	0.986
$\Lambda p\ \alpha_{e\nu}$	0.007 ± 0.037 [c]	-0.040	0.053
$\Lambda p\ \alpha_e$	$0.13\ \pm0.06$ [c]	0.016	0.066
$\Lambda p\ \alpha_\nu$	$0.82\ \pm0.06$ [d]	0.995	0.967
$\Lambda p\ \alpha_p$	$-0.51\ \pm0.07$ [d]	-0.601	-0.614
$\Sigma^- n\ \alpha_e$	$0.04\ \pm0.30$ [e]	-0.692	-0.424
θ_V (rad)	···	0.236 ± 0.004	0.257 ± 0.005
θ_A (rad)	···	···	0.213 ± 0.007
F	···	0.466 ± 0.009	0.510 ± 0.009
D	···	0.809 ± 0.009	0.763 ± 0.009
λ	···	1.0	1.0
$\chi^2{}_{\min}$	···	28.56	19.71
Prob.	···	1.3%	10.4%

[a] See Ref. 9.
[b] See Ref. 10.
[c] See Ref. 11.
[d] See Ref. 12.
[e] See Ref. 13.

and θ_A, together with λ if it is left free. First, we have considered the case when λ is fixed at unity. The results are

$$\begin{aligned} F &= 0.510 \pm 0.009\,, \\ D &= 0.763 \pm 0.009\,, \\ \theta_V &= 0.257 \pm 0.005\,, \\ \theta_A &= 0.213 \pm 0.007 \end{aligned} \tag{5}$$

at a C.L. of 10.4% ($\chi^2_{\min} = 19.71$) for 13 degrees of freedom. The predicted values are given in column four of Table I. See also Ref. 16. If λ is also fitted, it is fixed at 0.95 ± 0.82 at a C.L. of 7.7% ($\chi^2_{\min} = 19.71$) for 12 degrees of freedom. The values of F, D, θ_V, and θ_A are not changed.

The two angles are distinctly separated by many times their error bars (about six times). There is an improvement of these fits over the one-angle fit, although it is not an impressive one. Five of the predicted quantities are off the error bars of their experimental counterparts. The neutrino asymmetry in Λ beta decay is almost two standard deviations off. F, D, θ_V, θ_A, and χ^2 seem insensitive to the variation of λ, so the C.L. is lowered when λ is allowed to vary. However, the pleasant aspect is that λ is fixed at a reasonable value compatible with axial-vector-meson dominance, in contrast with the one-angle fit.

The axial-vector angle θ_A needs an interpretation. It is not clear that there are two intrinsically different Cabibbo angles. The difference between the two can be due to symmetry-breaking effects, but then one would expect that $|\Delta S| = 1$ decays would be more affected by symmetry breaking than $\Delta S = 0$ decays. If one chooses this interpretation, then $\theta_A \neq \theta_V$ only for $|\Delta S| = 1$ decays. This would be a phenomenological way[3,4] to introduce symmetry-breaking effects other than through the masses. We have also tried this possibility. For $\lambda = 1.0$, the results are

$$\begin{aligned} F &= 0.515 \pm 0.009\,, \\ D &= 0.771 \pm 0.009\,, \\ \theta_V &= 0.257 \pm 0.005\,, \\ \theta_A &= 0.211 \pm 0.07\,, \end{aligned}$$

again at a C.L. of 10.4% ($\chi^2_{\min} = 19.71$). Fitting λ changes nothing; it is fixed at 0.99 ± 0.82. In these two cases the predicted quantities agree with those of column four in Table I, except for changes in the third decimal place. So, from this point of view one cannot say whether the difference between θ_A and θ_V is intrinsic or due to symmetry breaking. The two-angle fits have a better C.L. than the one-angle fit, but still they are rather poor. Therefore, we think that the current experimental evidence makes it worthwhile to investigate symmetry-breaking corrections to Cabibbo's model.[18]

IV. DISCUSSION

In the present test of Cabibbo's model we have found that there are some deviations between the model and the available data in hyperon semileptonic decays. In view of this, we have investigated whether these deviations could be attributed to the existence of two different vector and axial-vector Cabibbo angles, or to the q^2 variation of the form factors, or to both. Although the agreement with the data is somewhat improved, we cannot say it is completely satisfactory.

We find the above analysis stimulating for both theory and experiment. It is clear that the angular coefficients do provide a more stringent test of Cabibbo's model. However, we should wait until other independent measurements of such coefficients are made before we reach a definite conclusion. In the meantime, the present data are encouraging enough to make hyperon semileptonic decays good grounds to study symmetry breaking.

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PHYSICAL REVIEW D VOLUME 9, NUMBER 1 1 JANUARY 1974

Tests of charge symmetry and scaling in neutrino physics*

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Recent theories of weak interactions require a weak current which strongly violates the usual charge-symmetry requirement. We explore the consequences of this fact for deep-inelastic neutrino and antineutrino scattering assuming the validity of Bjorken scaling.

We examine the consequences of charge symmetry and scaling for inclusive neutrino and antineutrino scattering on targets with roughly equal numbers of protons and neutrons. These are the first experiments for which accurate data are becoming available. We are motivated by recent developments in weak-interaction theory[1] which appear to require large departures from charge symmetry.

The strangeness-conserving weak hadron current is often assumed to be charge-symmetric; after an isotopic rotation by 180° it becomes its Hermitian adjoint. Support for this hypothesis at low energy is found in β decays of mirror nuclei,[2] and in the $\Delta Y = 0$ β decays of Σ hyperons.[3] In inelastic ν and $\bar{\nu}$ scattering from nucleons, where larger energy and momentum transfer are involved, only small departures (of order $\tan^2\theta_C \sim 5\%$) are expected from the strangeness-changing part of the Cabibbo current. But, there are theoretical reasons to believe that the Cabibbo current is not the entire weak hadron current. The small value of the neutral-kaon mass splitting, and the known suppression of strangeness-changing neutral leptonic decay modes seem to require that there be an extra part of the weak hadron current which is isoscalar (and, hence, not charge-symmetric), and which changes charm, a conjectured new quantum number conserved by the strong and electromagnetic interactions.[4] Generally, the charm-conserving Cabibbo current and the charm-changing addition must have the same coupling constant, but only the Cabibbo current can be effective below the threshold for production of charmed particles. Aside from small effects of order $\tan^2\theta_C$, inelastic ν ($\bar{\nu}$) scattering should satisfy charge symmetry when W (the mass of the final hadron state) is below M_c (the mass of the lightest-charmed final state), but large departures may appear for $W > M_c$. The value of M_c must be above ~2 GeV since charmed states have not yet been found, and it must be below ~4 GeV to provide enough suppression of forbidden processes.[4] It is our purpose here to describe how best to look for these violations of charge symmetry in inclusive neutrino experiments.