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BRANCHING RATIO AND FORM OF INTERACTION FOR THE BETA DECAY OF THE Λ HYPERON

C. Baglin, V. Brisson, A. Rousset, J. Six
Ecole Polytechnique, Paris

H.H. Bingham*, M. Nikolić, K. Schultze
CERN

C. Henderson, D.J. Miller, F.R. Stannard
University College, London

R.T. Elliott, L.K. Rangan
Rutherford Laboratory, Chilton

A. Haatuft, K. Myklebost
University of Bergen, Norway

Abstract

102 events of the decay $\Lambda \rightarrow p+e^{-}+\nu$ have been found among 218,000 photos taken with the Ecole Polytechnique 1x1/2x1/2 m^3, 17 Kilo Gauss heavy liquid bubble chamber in a 1.45 GeV/c K^- beam ($< 2^o/o\ \pi^-$) at the CERN PS. The liquid was genetron C_2F_5Cl, density 1.2 gm/cm^3, radiation length 25 cm, giving $\sim 87^o/o$ electron detection efficiency and stopping $\sim 85^o/o$ of protons from $\Lambda \rightarrow p+e^{-}+\bar{\nu}$.

The branching ratio $(\Lambda \rightarrow p+e^{-}+\bar{\nu})/(\text{All}\Lambda)$ is found to be $0.78 \pm 0.12 \times 10^{-3}$ in agreement with previous results[1]. The proton transverse momentum (and proton kinetic energy in the Λ rest system) spectra, and the e-ν correlation are incompatible ($< 1^o/o$ probability) with those expected for either pure vector or pure scalar $\Lambda \rightarrow p+e^{-}+\bar{\nu}$ interaction. Pure tensor or pure axial vector are less probable than V±A, but are not excluded by the data. Assuming a V and A theory with two form factors independent of the momentum transfer, the best fit is for $|C_V/C_A| = 0.8^{+0.9}_{-0.8}$ and with $95^o/o$ confidence $0 < |C_V/C_A| < 3$. Since these Λ's are unpolarized the sign of C_V/C_A is not determined.

* FORD Foundation Fellow

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I. Introduction

Prior to our experiment, it was known[1,2] that the beta decay of the Λ hyperon ($\Lambda \rightarrow p+e^{-}+\nu$) proceeds at a rate roughly an order of magnitude slower than that predicted by a straightforward extension of the V-A theory of the weak interactions[3]. No spectra or correlations had been measured, however, so little was known about the form of the interaction responsible for the decay. Since publication of our preliminary results[4], which confirmed previous measurements of the branching ratio, and gave the first indications as to the form of the decay interaction, a measurement of the sign of C_V/C_A (negative as in neutron beta decay) has been reported[5] along with confirmation of our results for the form of the interaction (pure S and pure V ruled out, V$\pm$A more probable than pure A or pure V). At least two other experiments[6,7] are in progress to improve knowledge of the form of the Λ_β decay interaction. Meanwhile, some explanations for the low Λ_β rate have appeared[7-11]. Cabibbo[8], for example, predicts on the basis of a unitary symmetry model that the branching ratio $\Lambda \rightarrow pe^{-}\nu$/All$\Lambda$ should be about 10^{-3} and that the decay interaction should be approximately of the V-A form.

In this paper, we summarize the final results of our analysis of 102 events of $\Lambda \rightarrow p+e^{-}+\bar{\nu}$ found among 218,000 photos taken with the Ecole Polytechnique heavy liquid bubble chamber[12] (dimensions 1x1/2x1/2 m^3, magnetic field 17 Kilo Gauss, liquid C_2F_5Cl, density 1.2 radiation length 1/4 m). The CERN 28 GeV Proton Synchrotron was used to provide the electrostatically separated beam[13] of 1.45 GeV/c K^- giving $\sim$ 3 K^- interactions and $\sim$ one Λ^0 (of average momentum 0.6 GeV/c) per photo.

II. Selection of events - background

The large size and magnetic field of the bubble chamber and its dense, short radiation length liquid permit almost unambiguous visual identification of $\Lambda \rightarrow p+e^-+\nu$ events, directly at the scanning stage. For the Λ's produced in this experiment (average momentum ~ 0.6 GeV/c) most (~ 85°/o) protons stop in the liquid and are identified by curvature-ionization - residual range information as well as by absence of decay or interaction products at the stopping point. Most (~ 87°/o) electrons are identified by their characteristic spiral stop (at minimum ionization) in the chamber, due to rapid energy loss by radiation.

At the scanning stage V^o_β events were accepted for further study, whether or not the proton was identified, if the electron (or positron) track in projection went through a radius vector maximum or "Rmax" (Fig.1). The electron detection efficiency by this method is 87°/o and essentially all π's and μ's, etc., are rejected. A cut-off on projected lambda-length (L_Λ in Fig.1) eliminated all events with $L_\Lambda > 20$ cms ($\gtrsim$ three mean lives). 170 events with negative electrons satisfied both tests and were accepted as Λ^o_β candidates.

To eliminate events with poor measurability we required $L_\Lambda > 0.5$ cms and $L_p > 0.5$ cms or, if the proton went out or interacted, $L_p > 10$ cms. To eliminate K^o_β events and Λ^o_β's with spurious origins we required the transverse proton momentum P_T to be less than its theoretical maximum (163 MeV/c) or compatible with it within two standard deviations. The significant sources of background still remaining at this stage were as follows:-

1) $$K^o \rightarrow \pi^+ + e^- + \bar{\nu}$$

~ 85°/o of Λ^o_β protons stop in the chamber, and so cannot be confused with background π^+s. Similarly, most of the π^+s slow down or stop with characteristic curvature in excess of that possible for protons. However, for those higher energy K^o's which happen to decay with small transverse momentum, there is still a problem. This was solved by retaining only those Λ_β's that after kinematic reconstruction had momenta less than

1 GeV/c. With such a criterion outgoing protons of more than 10 cms length are almost always distinguishable from π^+'s by ionization. The remaining K^o background is estimated to be less than 1°/o. (This is verified by the fact that among the $K^o \rightarrow \pi^- + e^+ + \nu$ events found during the same scanning, no event is compatible with the decay $\bar{\Lambda} \rightarrow \bar{p} e^+ \nu$ after application of the corresponding criteria.)

2) $\Lambda^o \rightarrow P + \pi^-$
$\quad\quad \hookrightarrow \mu^- \rightarrow e^-$

This background cannot be completely eliminated. About 3°/o of π^- decay to μ^- in flight, most ($\sim$70°/o) of the μ^- stop in the chamber and about 3 out of 4 stopping μ^- decays to $e^- \nu\bar{\nu}$ rather than be absorbed. Care was taken to detect abrupt changes of bubble density across visible kinks in the negative tracks. Events with such changes, or with a kink greater than 15° on the negative tracks were rejected. About 10°/o of $\pi \rightarrow \mu\nu$ decays are such that the kink is $<$ 15°. The stopping μ is recognized by ionization in about 3 out of 4 cases and the μ-e angle is $<$ 15° only $\sim$ 1.7°/o of the time. Thus about one Λ^o in 60,000 should contribute to this background. Corresponding to our cut-offs we have about 120,000. $\Lambda \rightarrow p\pi^-$, so we expect about two such background events.

3) Neutron interactions giving a proton plus a β-decay electron from the residual nucleus.

The highest possible electron energy is 13 MeV for the decay of B^{12}. This background is eliminated by rejecting events with laboratory electron energy less than 20 MeV. Other background processes (e.g. neutron star plus e^- from Dalitz pair) were found to be negligible, i.e. $\ll$ 1°/o.

Thus, we obtained a very pure ($>$ 96°/o) sample of 102 Λ_β's, of which 87 had a stopping proton.

III. Branching ratio

Subtracting $3^{\circ}/o$ $\Lambda \to p+\pi^-$ (with $\pi^- \to \mu^- \to e^-$) background events, adding $2^{\circ}/o$ electrons lost due to kinks $> 15^{\circ}$, and $4^{\circ}/o$ cut due to energy $<$ 20 MeV, correcting for electron detection efficiency ($87^{\circ}/o$) and scanning efficiency ($85^{\circ}/o$ based on a re-scan of $\sim$ half the film), we find the corrected number of Λ^{o}_{β}'s in the experiment is (138±17). (The correction for protons cut due to range $<$ 5mm is $\sim 7^{\circ}/o$, but the same cut-off was applied to the normal Λ's, so only the difference, $\sim 1^{\circ}/o$ is taken into account.)

The number of normal-mode Λ^{o} decays was estimated by counting the number of V^{o}'s found throughout the film. A random sample of V^{o}'s was then measured to determine the proportion of these events that were examples of $\Lambda^{o} \to p+\pi^-$ satisfying the L_{Λ}, L_{P} and P_{Λ} cut-off criteria.

The total number of Λ's, including those decaying by the neutral mode, (assumed 1/2 as frequent as the charged mode) was found to be (177,000±10,500). The branching ratio is therefore

$$R = \frac{\Lambda^{o} \to P+e^- +\bar{\nu}}{(\Lambda \to P+\pi^-) + (\Lambda \to n+\pi^{o})} = \frac{138 \pm 17}{(177,000 \pm 10,500)}$$

$$= \underline{(0.78 \pm 0.12) \times 10^{-3}}$$

IV. Reconstruction of the events

For each event the Λ direction (λ_Λ, φ_Λ) and the momentum and direction of the proton and electron are measured. The directions are typically determined to $\sim 2^{\circ}$. The proton momentum is determined to $\sim 2^{\circ}/\mathrm{o}$ (using a range momentum table tested previously[14]) and the electron momentum by curvature to $\sim 35^{\circ}/\mathrm{o}$ (after correction for bremsstrahlung effects by a method tested independently[15]). The Λ momentum (P_Λ) is unknown since the Λ are produced on heavy nuclei.

In applying energy and momentum conservation (4 equations) at the Λ decay point, there are no extra constaints on the four unknown quantities, P_Λ and (P, λ, φ) of the neutrino. There are two solutions to the equations and thus two possible reconstructions of the event in the Λ rest system. (Note, however, that the two reconstructions are identical when projected on to the plane perpendicular to the Λ line of flight.) Also, there is only one solution for the neutrino momentum in the Λ rest system and the two solutions for the electron momentum differ only slightly. Because of the large errors on the electron momentum measurements, the solutions were imaginary in $\sim 40^{\circ}/\mathrm{o}$ of our cases. A least squares adjustment of the measured quantities (principally of the electron momentum, and of the angle between the proton and the Λ) was done in these cases to obtain a real solution. Correction for possible systematic effects of this fitting procedure was done using Monte Carlo generated fictitious Λ_β events as discussed below.

Each event was weighted by the inverse probability of its electron having an Rmax (Fig.1) in the chamber. Effects of bremsstrahlung, multiple and single scattering, etc., were taken into account, as described in Reference 1. The average weight was 1.14, no weight was > 3, and the effect of the weighting was quite uniform over the proton spectra and e-ν correlation distributions.

Corrections for cut-offs on L_Λ, P_Λ, etc., which do not bias the spectra, have been ignored, of course. Small ($< 2^{\circ}/\mathrm{o}$) corrections for cut-offs on the proton and electron minimum momenta (200 MeV/c and 20 MeV/c respectively) have been included for the mean values of the varying spectra, but have not been included in the weights. The effects of these cut-offs have been included in the Monte Carlo generated theoretical distributions described below.

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V. Analysis for form of interaction

As is well known, the distributions most sensitive to the form of the interaction for unpolarised Λ's are cos $\theta^{*}_{e\nu}$ (Fig.2) and T^{*}_{p}, the proton kinetic energy in the Λ rest system. The two distributions are correlated, but contain some independent information.

We have used two separate means of treating the data which are quite differently sensitive to the possible biases, backgrounds and corrections discussed above. First we have used all the experimental information (in particular the rather poorly determined electron momentum) to reconstruct each event completely in the Λ rest system. Here we are especially sensitive to possible systematic errors in the electron corrections and in the fitting procedure, and we must take into account the two solutions for each event. We have done this by a Monte Carlo method, as described below. Second, we have studied the proton transverse momentum spectrum, as measured directly in the laboratory. Here we are especially sensitive to the angle between the proton and Λ directions (and to the proton length cut-offs), but there is no dependence on the electron measurements and there is no fit (and no two solution difficulty). The results of the two methods are quite compatible.

Analysis in the Λ rest system

The observed T^{*}_{p} and cos $\theta^{*}_{e\nu}$ spectra are shown in Figs. 3 and 4, for our 102 Λ_{β} events (both solutions are plotted). The theoretical spectra plotted for comparison include effects of the two solutions, our experimental resolution, and of various cut-offs. For this a Monte Carlo method was used to generate pseudo Λ_{β}'s at rest according to the form of the interaction to be tested: Scalar, Tensor, and various mixtures of Vector and Axial Vector[16-19]. Values for the Λ-momentum were chosen from a spectrum obtained by measuring a sample of Λ^{o} particles decaying by the normal mode. The pseudo-Λ_{β} events were transformed to the laboratory system, where the cut-offs were applied, and Gaussian errors on the measurable quantities were assigned. The events were then subjected to the same reconstruction procedure as had been used for the real events. "Test" histograms were obtained of T^{*}_{p} and cos $\theta^{*}_{e\nu}$ for each hypothesis. Where two solutions were found, each was added to the histograms with equal weight. For A, V-A and T, the spectra of spurious solutions were quite similar to those for the real solution. These test histograms derived from pseudo-events were finally compared with the histograms of data from the real events. The comparison with the test-distributions was made by means of a χ^2-fit with three degrees of freedom.

For scalar the χ^2 values corresponding to the T_P^* and cos $\theta_{e\nu}^*$ distributions were 20.2 and 17.9 respectively, (i.e. $< 1^\circ/o$ probability), while for tensor we found values of 2.5 and 3.8. The χ^2 values for V and A mixtures are shown graphically in Fig.5.

The mean values of T_P^* and cos $\theta_{e\nu}^*$ expected for the various interaction forms are given in Table 1, in comparison with our experimental values after corrections for the effects of fitting, of the various cut-offs and of the $\Lambda\pi\mu e$ background. These corrections are small, e.g. 0.2 MeV for (T_P^*), and 0.02 for (cos $\theta_{e\nu}^*$).

The electron and neutrino momentum spectra are shown as a check in Figs. 6 and 7. There is only one solution for the neutrino momentum: for the electron momentum the two solutions never differ by more than the experimental resolution and the average of the two solutions is plotted. These two spectra are compatible with the expected distributions[17], as modified by effects of our experimental resolution. The theoretical spectra are quite insensitive to the form of the interaction assumed (the $\sim 3^\circ/o$ difference between the electron and neutrino spectra, due to the V, A interference term, for example, is not observable with 102 events). The agreement ($\chi^2_e = 5.4$ and $\chi^2_\nu = 3.9$ for three degrees of freedom, respectively, i.e. $15^\circ/o$ and $30^\circ/o$ probability) of predicted with observed lepton spectra gives additional confidence in the corrections for electron bremsstrahlung, for electron detection efficiency, and in the fitting procedure.

Analysis in the laboratory system

Fig. 8 shows the unfitted proton momentum component, P_T, transverse to the Λ direction in comparison with the theoretical distributions[18,19]. P_T has the advantage that, by not having to transform to the Λ rest system, we overcome the two-solution ambiguity. P_T is independent of the comparatively poorly determined electron momentum but is, of course, very sensitive to the angle between the proton and Λ directions. The P_T distribution is simply related to that of T_P^*, although there is some loss of information through having to integrate over the solid-angle. (The distribution of the cosine of the angle between the proton and the Λ direction, in the Λ rest system, is uniform if the Λ has spin 1/2 and if parity is conserved at production. Any transverse polarization will not affect the transformation T_P^* to P_T.)

A subsidiary study of $\Lambda^o \rightarrow p+\pi^-$ events, whose spectrum for P_T is very similar to that for Λ_β's, gave data from which we determined the small experimental biases on the mean value of P_T due to the various cut-offs. The mean values of P_T for various theories, and the corrected experimental value are shown in Table 1.

The corrected mean value of the distribution of the fitted e-ν angle projected onto the plane transverse to the Λ direction is also compared (in Table 1) with the mean values expected for the several possible forms of the interaction[19).

VI. Conclusion

From Table 1, one sees that the results of the four spectra are quite consistent. On the basis of the mean values alone, Scalar and pure Vector interactions are ruled out with a certainty greater than 99°/o. Tensor is not ruled out, but is less probable than a range of V and A mixtures. The combined χ^2 probabilities of the fits of the various theoretical spectra (with experimental resolution folded in) to our observed proton and e-ν spectra are:

Vector < 1°/o	Axial Vector 35°/o	V±A 38°/o
Scalar < 1°/o		Tensor 15°/o

On the assumption that only V and A contribute, with constant form factors, the mean value of the proton transverse momentum spectrum and Fig.5 for the T_P^* and $\cos\theta_{e\nu}^*$ distributions give excellent agreement for the ratio of the Vector and Axial Vector form factors. The best value is:

$$\left|\frac{C_V}{C_A}\right| = 0.8\,^{+0.9}_{-0.8}$$

and with > 95°/o confidence

$$0 \leqslant \left|\frac{C_V}{C_A}\right| \leqslant 3.$$

Of course, a range of S and T mixtures would fit the data equally well.

We find for the branching ratio

$$\Lambda \rightarrow pe^-\nu/\text{All}\Lambda^0 = 0.78 \pm 0.12 \times 10^{-3}$$

confirming the value of $0.82 \pm 0.13 \times 10^{-3}$ given by a previous experiment[1)], and in agreement with the predictions, for example, of Cabibbo[8)].

Table 1

	S	T	V	A	V±A	Experiment
$\langle P_T \rangle$	81	98	106	89	93	92± 4 MeV/c
$\langle T_P^* \rangle$	6.6	8.2	9.1	7.5	8.1	8.1±0.3 MeV
$\langle \cos \theta^*_{e\nu} \rangle$	-0.28	+0.01	+0.15	-0.16	-0.04	-0.07±0.08
$\langle \cos \theta^*_{e\nu} \rangle_{PROJ}$	-0.36	+0.5	+0.22	-0.18	-0.04	-0.11± 0.10

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