PHYSICAL REVIEW VOLUME 137, NUMBER 5B 8 MARCH 1965

Form of the Interaction in Lambda-Hyperon Beta Decay*

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(Received 19 October 1964)

The form of the Λ_β-decay interaction was studied by using lambdas produced by stopping K^- mesons in the Berkeley 30-in. propane-freon bubble chamber. A selected sample of 59 Λ_β decays were analyzed in the Λ rest system, and 50 of these were further studied in the laboratory system. The results show that a pure tensor interaction can be ruled out with 98% confidence, and for mixtures of vector and axial vector, $|C_A/C_V|$ is greater than 0.7 with 95% confidence. Scalar and pseudoscalar, either alone or with small admixtures of tensor, cannot be ruled out. Pure axial-vector and $V\pm A$ are consistent with the data.

INTRODUCTION

THE results presented here are from a further analysis of the $\Lambda\rightarrow p+e+\bar{\nu}$ events used in finding the Λ_β branching ratio.[1] K^- mesons from the Bevatron were stopped in the Berkeley 30-in. heavy-liquid bubble chamber[2] filled with a mixture of 24% propane and 76% freon CF_3Br by weight. Of the events used for determining the branching ratio, 59 satisfied the more stringent criteria that were applied. The analysis was done in both the laboratory and Λ rest systems. The data show that a pure tensor interaction can be ruled out with 98% confidence, and for mixtures of vector and axial vector, $|C_A/C_V|$ is greater than 0.7 with 95% confidence. Equal amounts of scalar and pseudoscalar, either alone or with small admixtures of tensor, cannot be ruled out. Pure axial vector and $V\pm A$ are consistent with the data.

With unpolarized lambdas, our statistics were too small to find the sign of C_A/C_V from the lepton spectra.

SELECTION AND MEASUREMENT OF EVENTS

The Λ_β decays used to study the interaction were identified by one of two scanning criteria: Either the electron track displayed a characteristically high curvature, or had a δ ray greater than 1 cm. The degree of curvature required for acceptance was defined by constructing a radius vector from the Λ-decay point to a point along the neagtive track and requiring the radius vector to pass through a maximum value before reaching the end of the track (Fig. 1). The events identified by δ rays were required to have an electron track longer than 15 cm. A description of the scanning criteria and background studies is given in Ref. 1.

The momentum of the electron, as determined from curvature measurements by using the theory of Behr and Mittner[3] or by total shower length, was accurate to 37% at best. Center-of-mass reconstruction therefore depended strongly upon accurate measurements of the proton momentum. For this reason, all events with protons which did not stop in the chamber were eliminated. The direction of the proton and the Λ are also very critical input parameters in the reconstruction. To ensure that the ptoton-Λ angle was reasonalby well determined (to approximately 5 deg), a cutoff of 0.5 cm was applied both to the Λ length (L_Λ in Fig. 1) and to the proton length L_p.

Fifty events were identified by electron curvature, and nine by δ rays. Each Λ_β event was measured at least twice and spatially reconstructed. Mean values of the quantities calculated from the different measurements of each event were used, which effectively increased the measurement accuracy.

In addition to the Λ_β decays, a sample of 770 normal ($\Lambda\rightarrow p+\pi$) decays were measured and fitted to give more information about the validity of assigned errors and to provide a lambda-momentum spectrum.

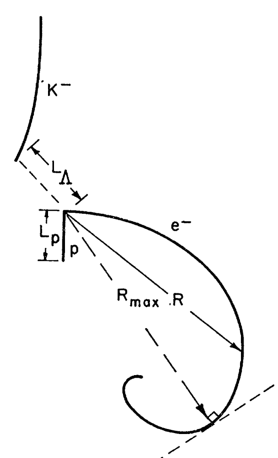

FIG. 1. Example of an $R_{\max}$ event. The radius vector **R** from the point of decay to a point on the electron track passes through a maximum value.

* This work was done under the auspices of the U. S. Atomic Energy Commission and the British Department of Scientific and Industrial Research.

[1] R. P. Ely, G. Gidal, G. E. Kalmus, L. O. Oswald, W. M. Powell *et al.*, Phys. Rev. **131**, 868 (1963).

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ANALYSIS OF THE FORM OF THE Λ_β INTERACTION

The Λ momentum could not be calculated from production kinematics, because of formation of the Λ's on heavy nuclei. The conservation of energy and momentum at the Λ_β-decay vertex gave a zero-constraint situation with two solutions for the Λ_β momentum. Since there was no way of choosing between the two solutions, they were treated with equal weight. For about 40% of our events, complex solutions occurred, owing to measurement errors. Usually this happened because the proton or electron transverse momentum was measured to be greater than the maximum theoretical value of 163 MeV/c. For these cases, the measured quantities were adjusted according to their errors by a least-squares procedure until the discriminant became zero, and a single real solution was obtained.

In the Λ rest system, the parameter most sensitive to the form of the Λ_β-decay interaction is the kinetic energy of the proton $T_p{}^*$ (see, for example, Ref. 4).

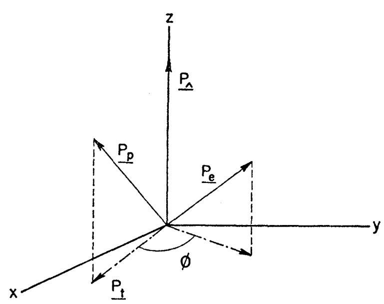

FIG. 2. Proton transverse momentum and angle Φ between the proton and electron in the plane transverse to the Λ line of flight. The Λ is shown moving along the positive z axis before decay. The x, y plane corresponds to the Λ transverse plane.

However, the distribution of $T_p{}^*$ is independent of interference effects between V and A, and therefore cannot be used to determine the sign of C_A/C_V.

The lepton spectra, though dependent on the form of the interaction and on interference effects, are dominated by the phase-space factor. This, coupled with the poor measurability of the electron momentum, precluded a determination of the sign of C_A/C_V in this experiment.

Results independent of electron momentum were obtained in the laboratory system from the distributions of proton transverse momentum (P_t), and of the angle Φ between the proton and electron measured in the plane perpendicular to the Λ line of flight (Fig. 2). These quantities were sensitive to the form of the interaction and had the advantage of having no two-solution ambiguity, and requiring no fitting.

STUDY OF BIASES AND EXPERIMENTAL RESOLUTION

Distributions of the Λ_β decay parameters in the laboratory system were biased by the selection criteria and by measurement errors, and in the Λ rest system also by the two-solution ambiguity and the fitting procedure. To compensate for these biases, we modified the theoretical distributions for different forms of the interaction by a Monte Carlo program, which generated events under simulated experimental conditions. The experimental results were then compared to the modified theoretical curves.

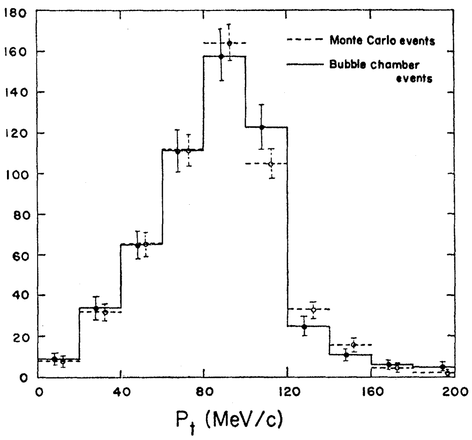

FIG. 3. Transverse-momentum distribution of 544 normal Λ decays selected from the sample of 770 measured events by applying cutoffs on L_Λ and L_p. The broken line is the P_t distribution of 1200 Monte Carlo events normalized to 544. The χ^2 probabliity for obtaining a worse fit is 30%.

The program initiated each random decay in the Λ rest system, according to a given matrix element. The proton and electron were then transformed to the laboratory system by using a Λ momentum chosen at random from a sample of 770 measured Λ decays. At this point the chamber geometry and range-energy relations were introduced, and the protons were required to stop within the chamber. Cutoffs were then applied on L_p and L_Λ, and each event was weighted according to the electron-detection efficiency curve.[1] Typical angle and track-curvature errors were assigned by random choice on the assumption that they were normally distributed.

The program was checked by having it produce normal Λ decays, with the "experimental" errors and cutoffs on L_p and L_Λ. The resulting distributions of P_t and $\Phi_{p\pi}$ (the angle between the proton and pion in the plane transverse to the Λ direction) agreed well with those from our measured sample of 770 Λ decays (see Figs. 3 and 4).

To obtain the quantities in the Λ rest system, the same program that had been used for the kinematical reconstruction of the real events was employed to find the two real solutions, or a fitted single solution for each Monte Carlo event.

Monte Carlo runs were made at seven different values of $|C_A/C_V|$ from 0 to ∞, i.e., throughout the range from pure vector to pure axial vector. For convenience, the parameter $Y=|C_A|-|C_V|/|C_A|+|C_V|$

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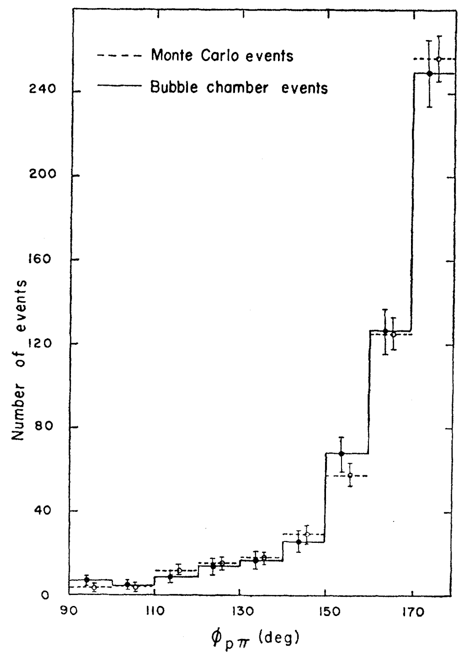


FIG. 4. Distribution of $\Phi_{p\pi}$ from the same events shown in Fig. 3. The χ^2 probability for obtaining a worse fit is 86%.

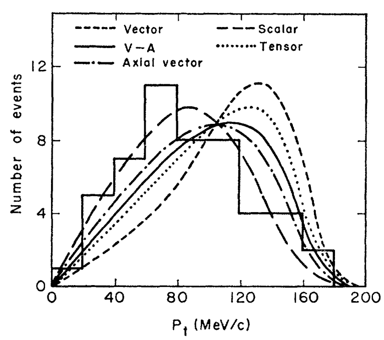


FIG. 5. Distribution of P_t from 50 R_{max} events. The smooth curves include the experimental resolution and biases.

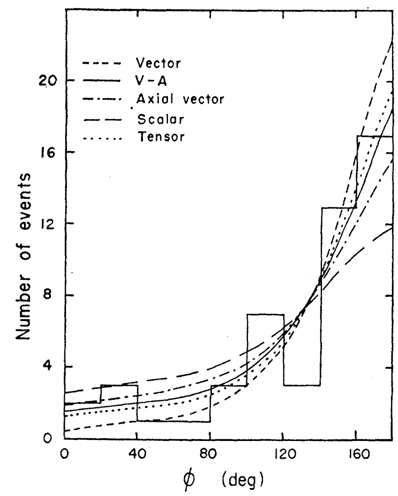


FIG. 6. Distribution of Φ from 50 R_{max} events. The smooth curves include the experimental resolution and biases.

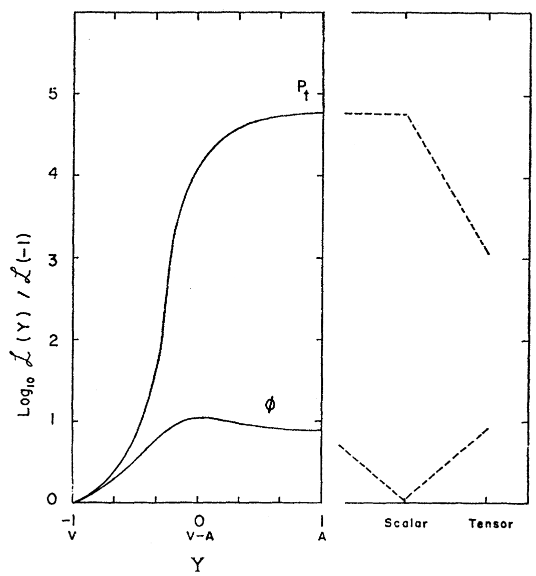


FIG. 7. Likelihood curves from P_t and Φ data from 50 R_{max} events. $Y=(|C_A/C_V|-1)/(|C_A/C_V|+1)$.

was used, so that $Y=-1.0$ for a pure vector interaction, $Y=0$ for $V\pm A$ and $Y=1.0$ for pure axial vector. Runs were also made using the tensor interaction and an equal mixture of scalar and pseudoscalar. In each case the induced form factors were assumed to be zero.

LABORATORY-SYSTEM ANALYSIS

For the laboratory-system analysis, δ-ray events were excluded. The remaining 50 events were all selected on the same basis, namely the R_{max} criterion. This sample was free from background, was selected with a high scanning efficiency, and had an electron-detection efficiency that was well-determined.[1]

Figures 5 and 6 show the data and the modified theoretical curves. The likelihood curves from the P_t

TABLE I. χ^2 probabilities for different forms of the interaction, from P_t and Φ data separately.

	Form of interaction								
	Vector	V-0.33A	V-0.67A	V-A	V-1.5A	V-3A	Axial vector	Scalar	Tensor
χ^2 of P_t distributions	26.7	16.7	8.5	5.4	3.8	2.8	2.3	0.2	10.1
Percentile from P_t (%)	$\ll 1$	<1	4	15	28	43	50	98	2
χ^2 of Φ distributions	4.3	3.0	0.25	0.07	0.24	0.54	0.75	4.29	0.25
Percentile from Φ (%)	23	39	97	>99	97	91	86	23	97

TABLE II. Mean values of theoretical distributions of P_t and Φ.

	Form of interaction								
	Vector	V-0.33A	V-0.67A	V-A	V-1.5A	V-3A	Axial vector	Scalar	Tensor
Mean P_t(MeV/c) from modified theoretical distributions Mean P_t from experiment$=86\pm6$	112	108	102	99	97	95	93	85	103
Mean Φ (deg) from modified theoretical distributions Mean Φ from experiment$=128\pm7$	141	137	132	128	126	124	123	116	132

and Φ data are shown in Fig. 7. Of the two quantities, P_t is more sensitive to the form of the interaction, indicated by the higher likelihood ratios of the P_t curve. That the maxima of these two curves do not coincide, can be accounted for by a large but reasonable statistical fluctuation. This is seen from the χ^2 analysis summarized in Table I and the comparison of mean values shown in Table II. In both cases the P_t data favor pure axial vector or scalar-pseudoscalar, while the Φ data favor $V\pm A$. However, Φ is not sensitive enough to rule out any of the possibilities.

The results from P_t indicate that a pure tensor interaction can be ruled out with 98% confidence. For mixtures of vector and axial vector, $|C_A/C_V|$ is greater than 0.7 with 95% confidence. A scalar-pseudoscalar interaction with small admixtures of tensor cannot be ruled out.

CENTER-OF-MASS SYSTEM ANALYSIS

The $T_p{}^*$ spectrum for the 59 events is shown in Fig. 8, together with five of the modified theory curves obtained from the Monte Carlo program. The likelihood ratio between the various V and A theories and pure vector is plotted in Fig. 9 as a function of Y. Figure 10 gives the χ^2 values for a five-cell fit between the $T_p{}^*$ spectrum and the modified theories. From this, with 95% confidence, we find that $|C_A/C_V|$ is greater than 0.4. A scalar-pseudoscalar interaction, a tensor interaction, or any mixture of the two is quite compatible with these results.

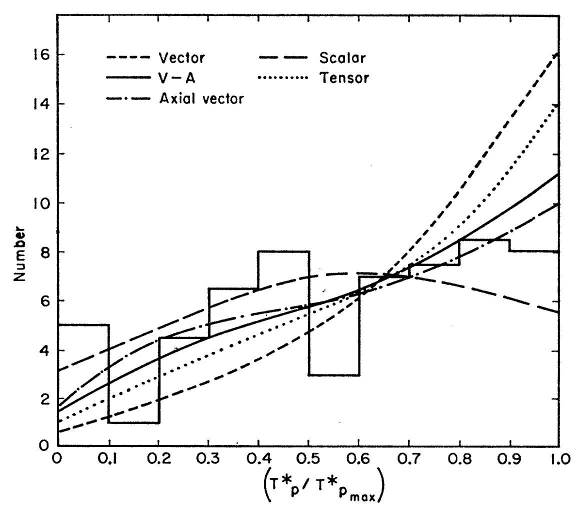
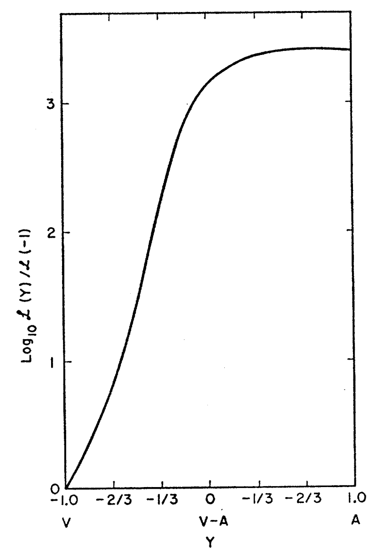


FIG. 8. Distribution of the proton kinetic energy in the Λ rest system for 59 events including δ-ray events. The smooth curves include the experimental resolution, the biases due to track length cutoffs, the two-solution ambiguity, and the effects of the fitting procedure.

FIG. 9. Likelihood curve from $T_p{}^*$ data for 59 events.
$Y=(|C_A/C_V|-1)/(|C_A/C_V|+1)$.



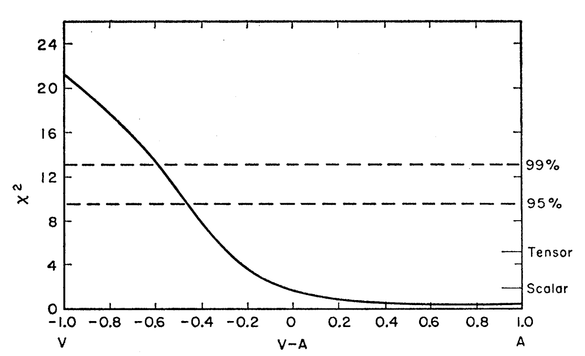


FIG. 10. Chi-square curve from $T_p{}^*$ data with four degrees of freedom. $Y=(|C_A/C_V|-1)/(|C_A/C_V|+1)$. Values for tensor and scalar-pseudoscalar interactions are shown at the right.

CONCLUSION

Results of the two analyses are consistent with each other and with previous experiments of Baglin *et al.*[5] and Lind *et al.*[6]

A value of $|C_A/C_V|=0.94$ predicted by Sakurai,[7] who assumed a Λ_β-decay branching ratio of 0.82×10^{-3}, is just compatible with our results. However, the value $|C_A/C_V|=0.72$ given by Cabbibo[8] is not in good agreement with our result from P_t which favors a predominately axial-vector interaction.

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ACKNOWLEDGMENT

We would like to thank Larry Oswald and the 30-in. chamber crew for all their efforts.

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PHYSICAL REVIEW VOLUME 137, NUMBER 5B 8 MARCH 1965

Inverse Compton Scattering of Cosmic-Ray Electrons

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(Received 29 October 1964)

It has long been known that an important mode of energy loss for cosmic-ray electrons is inverse Compton scattering with photons of starlight. Previous calculations of $\langle d\mathcal{E}/dt\rangle_{\rm av}$ due to this process have involved nonsystematic approximations involving the form of the Klein-Nishina formula and the angular distribution of the radiation as seen in the electron's rest frame. The present paper considers an electron of arbitrary energy in an isotropic thermal radiation field of temperature T. A formally correct expression for $\langle d\mathcal{E}/dt\rangle_{\rm av}$ is obtained as an asymptotic expansion in the quantity $\mathcal{E}kT/(m_ec^2)^2$ considered as a small parameter. The often quoted result $\langle d\mathcal{E}/dt\rangle_{\rm av}\propto\mathcal{E}^2$ is seen to be the zero-order term in this expansion. It is also seen that the energy-loss rate changes sign at an energy $\mathcal{E}\approx\frac{3}{2}kT$ as would be expected from thermodynamics. A derivation of the zero-order term is given from classical radiation theory, and from this it is seen that this term also describes the energy-loss rate due to synchrotron radiation as well as from inverse Compton scattering.

I. INTRODUCTION

THE scattering of energetic electrons by low-energy photons, called "inverse" Compton scattering, has been of astrophysical interest for many years. It was first investigated by Feenberg and Primakoff[1] as a process by which cosmic-ray electrons (and protons) would lose energy during their passage through the galaxy. Later Donahue[2] applied the general method of Feenberg and Primakoff to the case of electrons trapped in orbits about the sun.

The result of these two papers that the mean energy loss of an energetic electron of energy $\mathcal{E}$ is proportional to both the photon energy density and to $\mathcal{E}^2$ was applied by Hayakawa and Kobayashi[3] and by Hayakawa and Okuda[4] to the problem of the equilibrium of cosmic-ray electrons in the galaxy. More recently, Felten and Morrison[5] have considered this process as a possible source of galactic x rays[6–8] and gamma rays,[9–11] and Shklovsky[12] has proposed it as a source of x rays in solar flares.

In the calculations of Feenberg and Primakoff and of Donahue the relevant cross-section formula is the Klein-Nishina formula $\sigma(\epsilon',\chi')$ for the scattering of a photon of energy ϵ' by a *stationary* electron through an angle χ'. In essence the scattering probability is expressed in the electron's rest frame and then transformed to the laboratory frame to determine the mean energy transferred from the electron to the photon. In the previous calculations the full Klein-Nishina formula was not used but rather the asymptotic forms for $\epsilon'\ll m_ec^2$ (Thompson scattering) and for $\epsilon'\gg m_ec^2$. In Feenberg and Primakoff the two forms are used in the

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