Session VII

WEAK INTERACTIONS

Chairman: C. N. Yang

LEE: Introductory survey.

In addition to the strong and electromagnetic interactions, there exists a large class of interactions characterized by coupling constants of order 10^{-13}. This class of weak interactions can be divided into two distinct groups. The first group contains processes not involving neutrinos, while the second group consists of processes in which neutrinos participate. Particles involved in the first group also participate in the strong interactions, and therefore each of these particles has a well-defined value of isotopic spin I and its z – component I_z. The weak interactions in the first group are further characterized by the selection rule $\Delta I_z = \pm \frac{1}{2}$, which of course is identical with non-conservation of strangeness. The interactions in the second group involve leptons that do not participate in any strong interactions and, in contrast with the particles of the first group, no useful assignment of isotopic spin to these leptons has been found. In spite of this difference, all weak interactions seem to have striking features in common, such as the similarity in the strengths of the coupling constants and the recently observed violation of conservation of parity and charge conjugation. While non-conservation of parity and charge conjugation have been proved only for reactions in the second group, there are strong suspicions that this is true also for the reactions in the first group - I allude, for instance, to the τ- θ puzzle.

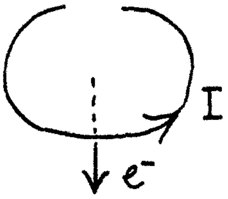
I shall first review briefly the present experimental status of the violation of conservation laws, together with the immediate theoretical implications. Next I shall develop some further theoretical considerations and speculations, and the particular points of view I shall adopt are fully shared by Prof. Yang.

I. The Experimental Situation

The first experiment demonstrating the non-conservation of parity and charge conjugation was performed by the Columbia and NBS groups, and involved the beta decay of polarized Co^{60} nuclei according to the reaction

$$Co^{60}\ (\text{polarized}) \longrightarrow Ni^{60} + e^- + \nu .$$

The alignment of the Co^{60} nuclei at low temperature was achieved by a magnetic field, and the electrons were found to be emitted preferentially in a direction antiparallel to the nuclear spin. From this asymmetry one can immediately deduce that parity is not conserved in the process, without invoking any detailed theory of beta decay. In fact, the direction of the magnetizing current loop together with the



preferential direction of the emitted electrons can be used directly to establish the difference between a right-handed coordinate system and a left-handed coordinate system. Furthermore, from the observed magnitude of the asymmetry one can conclude that charge conjugation as well as parity is not conserved in this reaction. The transition is of pure Gamow-Teller type, so that only tensor coupling is involved. If C_T is the coupling constant for the part of the interaction which commutes with parity, and C_T' is the coupling constant for the part which anticommutes with parity, then the relationship

$$C_T' \simeq -C_T$$

would account for the observed asymmetry.

The second confirmation of non-conservation of parity and charge conjugation came from the measurement of the angular distribution of electrons from $\pi - \mu - e$ decay; the experiments were done at Columbia and Chicago. The pion decays into a muon, which then decays into an electron:

$$\pi^{\pm} \longrightarrow \mu^{\pm} + \nu \quad (\text{or } \bar{\nu})$$
$$\mu^{\pm} \longrightarrow e^{\pm} + \nu + \bar{\nu} \ .$$

The angular distribution of the electrons with respect to the muon momentum was found to be asymmetrical, the electrons being preferentially emitted in a direction antiparallel to the muon momentum. The angular distribution is, apart from the depolarization effect, the same for both signs of the electric charge.

Following the initial experiments, a large amount of work was done on the longitudinal polarization of the emitted electrons, on the circular polarization of the associated gamma rays together with beta-gamma correlations, on the beta angular distributions from other nuclei such as Co^{58} and Co^{56}, and on $\pi - \mu - e$ decay with the muons stopped in many kinds of materials. All results seem to confirm rather conclusively the essential findings of the earlier experiments.

II. The Two-Component Theory of the Neutrino

The quantitative data on the violation of the conservation laws of parity and charge conjugation can be explained in a simple and appealing way by use of the two-component theory of the neutrino. This theory and its applications are by now well known, and I shall make only a few remarks about it.

(a) The two-component theory of the neutrino can be expressed, as a matter of convenience, in terms of the usual four-component Dirac theory of the neutrino, by imposing a subsidiary condition on the neutrino field ψ_ν :

$$\gamma_5 \psi_\nu = - \psi_\nu \ .$$

This ensures that the mass of such particles will be zero.

(b) In the two-component theory, the neutrino (which is the particle of the theory) will always have its spin parallel to its momentum. If we use this structure to define a right-handed coordinate system, then the neutrino always has right-handed spirality and the antineutrino always has left-handed spirality:

Neutrino: right-handed spirality (ν)

Anti-neutrino: left-handed spirality ($\bar{\nu}$)

For a given momentum, there exist only these two states.

(c) Let us describe the decay of Co^{60} in terms of these definitions. Since the electrons are seen to be emitted preferentially in a direction antiparallel to the spin of the Co^{60} nucleus, we conclude that $C' = -C$, where C and C' stand for the coupling constants of the parity conserving and non-conserving parts of the interaction in the conventional four-component theory. If we interpret this result in terms of the two-component theory we are led to the conclusion that the emitted neutrino particle has left-handed spirality, i.e. it actually is an anti-neutrino:

$$\mathrm{Co}^{60} \longrightarrow \mathrm{Ni}^{60} + e^- + \bar{\nu}.$$

The neutron decay process therefore is

$$n \longrightarrow p + e^- + \bar{\nu}.$$

Similarly, when we examine π-μ-e decay in the light of the two-component theory, we find that both a neutrino and an anti-neutrino must be emitted in the μ decay, not two neutrinos or two anti-neutrinos:

$$\mu^\pm \longrightarrow e^\pm + \nu + \bar{\nu}.$$

This can be shown by computing the Michel parameter ρ from the electron spectrum in the two cases. In the former case we get $\rho = .75$, while in the latter case we get $\rho = 0$ which is certainly ruled out by the experimental evidence. The best experimental value to date is $\rho = 0.68$. While the value of .75 is somewhat higher than the experimental one, the theory nevertheless predicts an electron angular distribution and an energy dependence of that distribution which are in reasonable quantitative agreement with experiment.

(d) Another very interesting conclusion to be drawn from the two-component theory concerns the expected longitudinal polarization of the electrons. The electron-neutrino coupling term (not involving derivatives) has the general form $\psi_e^\dagger \mathcal{O}_i \psi_\nu$, where $\mathcal{O}_i$ may be the scalar, tensor, vector, etc. operator. Using the subsidiary condition we may write

$$\psi_e^\dagger \mathcal{O}_i \psi_\nu = \frac{1}{2} \psi_e^\dagger \mathcal{O}_i (1-\gamma_5) \psi_\nu$$

$$= \frac{1}{2} \psi_e^\dagger (1 \pm \gamma_5) \mathcal{O}_i \psi_\nu \begin{cases} + \text{ for } S, T, P \\ - \text{ for } V, A \end{cases}$$

One can easily show that this interaction leads to a longitudinal polarization of the electrons given by

$$\langle \vec{\sigma} \cdot \hat{p} \rangle_{e^-} = \begin{cases} -\frac{v}{c} & \text{for } S, T, P \\ +\frac{v}{c} & \text{for } V, A \end{cases}$$

Thus if the interaction is scalar, tensor, or pseudoscalar, the emitted electron will have left-handed spirality; if the interaction is vector or axial vector, then it will have right-handed spirality. Now we know that beta decay occurs predominantly through scalar and tensor interactions, and consequently we expect the electron to have left-handed spirality. For positrons, of course, the opposite is true. These predictions have been verified experimentally for Gamow-Teller transitions.

(e) Even though the two-component theory describes the experimental phenomena very well, we may ask whether it could also account for the other conceivable reaction

$$n \longrightarrow p + e^- + \nu$$

where the spirality is opposite to the observed one. Indeed, the mere use of two-component theories does not exclude such possibilities. However, if both reactions exist at the same time we would have a non-zero rate for double beta decay, and the observed asymmetries would not attain their maximum possible values. In fact, as we shall hear from Prof. Case tomorrow, by using a less restricted Majorana form of the two-component theory we can extend it to get a non-zero neutrino rest mass. Yet experimentally we find that the mass is small, that the rate of the double beta process is also small, and that the asymmetry in the angular distribution is large. We therefore are led to ask whether an underlying principle is behind all this. Indeed, the evidence points very strongly to the law of conservation of leptons. This law and the two-component theory together imply three things:

1. The mass of the neutrino is zero.
2. The rate of the double beta process is zero.
3. Conservation of parity is violated, and the resulting asymmetries can attain their maximum values.

These statements seem to be in good agreement with experiment, and therefore we next turn our attention to the lepton conservation law.

III. The Law of Conservation of Leptons

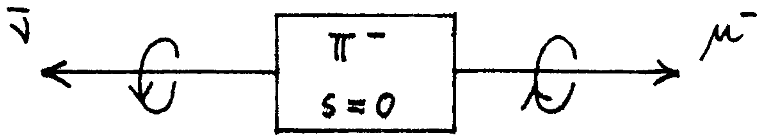
This law states that whenever a light fermion is emitted, another one is annihilated or an anti-fermion is emitted. We thus may assign a leptonic number to light fermions and anti-fermions, the signs being opposite in the two cases, and are led to the conservation of leptonic number.

By inspecting the beta decay process we find that the leptonic number for the neutrino is the same as that for the electron, and the decay of the muon tells us that μ^- and electron have the same leptonic number. The lepton conservation leads to several immediate theoretical predictions.

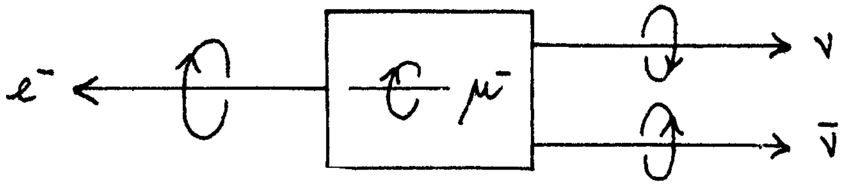
We consider the decay of the negative pion,

$$\pi^- \longrightarrow \mu^- + \bar{\nu}\,,$$

and draw a diagram showing the spiralities of the emitted particles:



Here a μ^- is created, and hence an antineutrino must also come out. Since the latter has left-handed spirality, and since the pion has spin zero, the μ^- emitted must have left-handed spirality to conserve total angular momentum. Next we draw a similar diagram for the subsequent decay of the muon, $\mu^- \longrightarrow e^- + \nu + \bar{\nu}$;

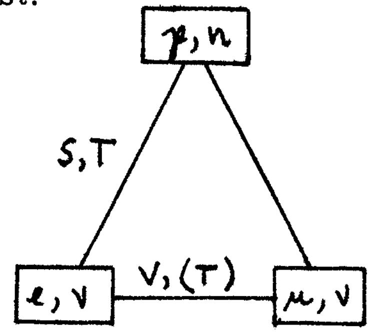


Since the electrons are emitted predominantly in the backward direction with respect to the muon momentum, and since we are merely interested in getting correct signs, we have drawn for simplicity only the high energy electron coming out in the backward direction, with the neutrino pair proceeding in the forward direction. The spiralities in the neutrino pair cancel, and conservation of angular momentum then tells us that the electron has the same spin component as the muon. Thus the e^- emitted in μ^- decay has right-handed spirality. Both of these predictions may of course be confirmed experimentally.

Let us assume that the above is correct, and look for further implications. The decay electron has right-handed spirality, and if in the interaction the electron and neutrino fields are coupled together, then by the arguments of Section II(d) the coupling must be vector or axial vector. In this case the vector and axial vector interactions are exactly the same, since the extra γ_5's operating on the ψ_ν in each of the (e, ν) and (μ, ν) factors simply produce compensating changes in sign. Thus the coupling contains vector, but not scalar or pseudoscalar or tensor parts. However, an antisymmetrical tensor of second rank is equivalent to a six-vector, and by virtue of the peculiar properties of the two-component neutrino three of its space components precisely cancel three of its time components. Consequently we may either say that there exists no tensor interaction, or that there is a tensor interaction with a non-vanishing coupling constant but what is multiplied by that coupling constant happens to be zero.

IV. The Universal Fermi Interaction

We next turn to the Universal Fermi Interaction, which is an attempt to gain a more unified understanding of certain of the weak interactions. We draw the famous triangle representing the interactions of interest:



Beta decay information tells us that the interaction between (p, n) and (e, ν) is scalar and tensor, while the two-component neutrino theory plus the law of conservation of leptons implies that the coupling between (e, ν) and (μ, ν) is vector. This means that the Universal Fermi Interaction cannot be realized in the way we have expressed it. If all these coupling types turn out to be experimentally correct, we prefer to think that the similarity in coupling constants cannot be accounted for in terms of such a limited scheme. Rather it is a universal feature of all weak interactions, and not just those involving leptons. Nevertheless, at this moment it is very desirable to recheck even the old beta interactions to see whether the coupling is really scalar, a point to which we shall return later.

We next consider the third leg of the triangle, the muon capture process:

$$\mu^- + p \longrightarrow n + \nu .$$

This process used to be hard to analyze because we only observed its rate, but the fact that the emitted neutrino carries away angular momentum can be used to gain more detailed information. The law of conservation of leptons tells us that a neutrino is emitted, not an anti-neutrino. For convenience let us assume that the captured muon is 100% polarized. Then the neutron angular distribution will not be isotropic, but will take the form $1 - \cos\theta$ for scalar and vector coupling, and $1 + \frac{1}{3}\cos\theta$ for tensor and axial vector coupling, where θ is the angle between the spin of the muon and the momentum of the neutron. Hence, by measuring this angular distribution we can get quite definite information on the coupling types for the third leg, and this is particularly important in view of the apparent coupling discrepancy in the other two legs. Further information on the nature of this process can be obtained by observing the bremsstrahlung emitted during the reaction

$$\mu^- + p \longrightarrow n + \nu + \gamma,$$

measuring the angular distribution together with the circular polarization of the gamma rays. The conclusions to be drawn from these considerations depend on further experiments. The present data seem fairly well accounted for by the two-component neutrino theory, and we may say that in a modest way we have some understanding of these phenomena. The same cannot be said, however, with regard to the decay of K mesons and hyperons, the topic to which we turn next.

V. The Decay of K-Mesons and Hyperons

(a) We first consider the $\tau - \theta$ puzzle. Once we have observed the non-conservation of parity and charge conjugation in some weak interactions, we are free to conjecture that these violations extend to the entire class. Therefore the $\tau - \theta$ duality can be explained in a simple way, perhaps even the correct way, by just saying that the θ particle is identical to the τ particle. In the decay of K-mesons into two or three pions we measure at most two independent momenta, going to the center of mass system in the three pion case. If the K-meson has no spin, then the parity conserving and non-conserving modes of decay can never interfere because we cannot form a pseudoscalar out of two momentum vectors. Consequently the maximum possible evidence that parity is not conserved in K decay is precisely what we have seen: a spinless particle decaying into two or three pions, the masses and lifetimes for the two cases being the same.

Nevertheless, several attempts have been made to base a theory on the idea that only reactions involving neutrinos violate parity conservation, and that reactions not involving neutrinos do not violate parity conservation. Under this assumption the Dalitz-Fabry plot tells us that the θ particle is not the same as the τ particle. We would then expect to have two particles with different lifetimes, contradictory to what seems to be observed. Thus there is definite experimental evidence against the idea that the K-meson exists in a parity doublet, and in fact there is no theoretical necessity for such a proposal. Assuming spinless particles, we then have in the case of τ and θ decay the maximum possible information on non-conservation of parity.

(b) We may hope to gain additional information from hyperon decay, since hyperons, being fermions, certainly have spin. Let us consider the production of Λ^0 :

$$\pi^- + p \longrightarrow \Lambda^0 + K^0$$

This is a strong interaction which we may regard as a polarizer of the Λ^0 . We then use the subsequent decay of the Λ^0 , which is a weak interaction, as an analyzer of this polarization:

$$\Lambda^0 \longrightarrow p + \pi^-$$

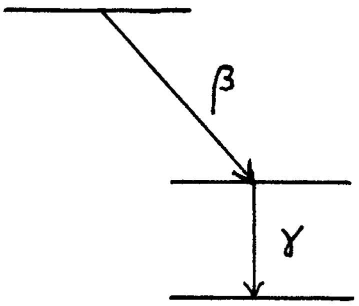
In fact, for this decay to serve as an analyzer at all, it must necessarily violate the conservation law of parity. However, since the polarizer is a strong interaction and since the analyzer involves slow particles, it is possible that neither polarizer nor analyzer are as effective as in the case of the leptons in π-μ-e decay, where the polarizer is known to be nearly 100% effective and the analyzer is also extremely effective. To illustrate, let us assume the spins of the Λ^0 and K^0 to be 1/2 and 0, respectively. If we carry out the production near threshold so that only S and P-waves are involved, and if the production angular distribution has the form $(1 \pm \cos\theta)^2$, then the polarization of the Λ^0 is zero for all angles. Here θ is the angle between the incoming pion momentum and the outgoing hyperon momentum in the center of mass system. Observation of course does not substantiate that this is the actual angular distribution. It is, however, the most peaked distribution in the forward or backward direction possible for S and P-waves, and may not be too far from the actual one. Here we would have a case in which the polarizer is not a very effective one. To obtain definite conclusions on the non-conservation of parity it is imperative to have good knowledge about polarizations. For that reason it will probably be very useful to investigate such production and decay processes in a bubble chamber near threshold energies.

(c) The θ_1^0 and θ_2^0 particles were introduced on the assumption of invariance under charge conjugation. Since this assumption is invalid for at least some of the weak interactions, we shall examine the implications of this violation on their expected behavior. From the strong production reactions we infer that there should exist two states (i.e. two particles) of θ^0 type, with strangeness + 1 and - 1. The existence of two states implies in general the existence of two lifetimes, and we wish to find out how the short-lived and the long-lived particles behave. Let us first assume that charge conjugation is not conserved, but that charge conjugation times parity is conserved. We immediately conclude that the short-lived particle can decay into two pions but the long-lived one cannot. The situation remains the same as under the original assumption, and evidently we cannot see a violation of charge conjugation invariance unless we see a violation of parity. If charge conjugation times parity is not conserved, the long-lived particle can decay into two pions but the 2 π to 3 π branching ratio, based on phase space arguments, would be quite small and the 2 π mode might escape experimental detection. The striking behavior of θ_1^0 and θ_2^0 thus happens to be an insensitive test body for non-conservation of C or CP.

VI. Time Reversal Invariance

The question of whether CP is or is not conserved brings us to the question of invariance under time reversal. According to the famous TCP theorem, if T is invariant then CP is invariant, and if T is not invariant then CP is not invariant. We have seen that θ_1^0 and θ_2^0 do not furnish a sensitive test for T invariance. Fortunately more sensitive tests exist in beta decay, and I shall mention only a few of these.

One method, involving the type of experiment already done, measures the beta angular distribution from polarized nuclei, determining $\vec{J} \cdot \vec{p}_e$ for a ($J \to J$, no) transition. This provides information about the real part of $|M_F||M_{GT}|(C_S C_T'^* + C_S' C_T^*)$. The imaginary part of this quantity can be obtained in a beta-gamma cascade



by measuring $\vec{J}\cdot(\vec{p}_e \times \vec{p}_\gamma)(\vec{J}\cdot\vec{p}_\gamma)$ or $\vec{J}\cdot(\vec{p}_e \times \vec{p}_\nu)$
A measurement of both the real and the imaginary parts for the same element would yield a great deal of information. Even the measurement of $\vec{J}\cdot(\vec{p}_e \times \vec{p}_\nu)$ alone will give much information. The real part of $|M_F||M_{GT}|(C_S C_T'^* + C_S' C_T^*)$ has been measured by the Leyden and NBS groups for Co^{58} , and was found to be zero. The ratio $|M_F|/|M_{GT}|$ had been determined previously, and neither M_F nor M_{GT} was found to vanish. Since C_S seems to be non-zero, and since certainly C_T is non-zero, it follows that the quantity in question is purely imaginary. This implies violation of time reversal invariance. But this argument is based on much experimental information obtained at different times, and it seems desirable to check all these results. Of course it would be extremely useful to measure the imaginary part directly, as outlined above. The question of the existence of the scalar interaction needs careful re-examination, and to that end a measurement of the spirality of the emitted positron is suggested. The answers, bearing on the existence of a Universal Fermi Interaction and on time reversal invariance, should be forthcoming in the near future.

VII. The Mach Principle

If it turns out (not to our great surprise, perhaps) that T is not invariant, what are the implications? This question leads us to a brief discussion of the Mach Principle which states that the laws of physics should not depend upon the choice of any particular geometrical coordinate system. If we believe in this principle then the present information on asymmetries can still be accounted for in two ways, depending on whether T is invariant or not. If T is invariant then CP is invariant, and when we perform mirror reflections we must simultaneously change particles to anti-particles to preserve the overall symmetry of space and time. We nevertheless have lost one symmetry property compared to the earlier situation. If T is not invariant then CP is not invariant, and changing particles into antiparticles does not help. But a firm believer in Mach's Principle might conjecture, for instance, that there exist two different kinds of nucleons. One kind of proton would be a right-handed one (p_R) and the other would be a left-handed one (p_L). They have opposite spirality. Our world consists almost 100% of one kind, which accounts for the observed asymmetry. But overall space symmetry can still be maintained by taking into account the p_L which do not exist in any appreciable quantity in our local cosmological region. Thus P is kept invariant, and from the TCP theorem we know that TC will be invariant, even though C is not invariant. Thus we can still have overall time reversal symmetry by changing particles to anti-particles.

The second possibility is certainly not so simple or attractive as the first.

In conclusion, let me emphasize again the curious nature of all weak interactions. In spite of their great diversity, they display striking similarities in the strengths of coupling constants, in the peculiar selection rule on I_z , and in the non-conservation of parity and charge conjugation. Perhaps all these are merely different aspects of a single and unifying principle underlying all weak interactions.

DISCUSSION

GELL-MANN: Would you elaborate a little more on the exact nature of the proposals concerning the possibility of different kinds of protons?

LEE: The conjecture is that p_R and p_L form a doublet structure with very low mutual transition rate. The oscillation time would be longer than the lifetime of the universe. For some reason having to do with the details of the creation of the universe we see predominantly only one kind.

GELL-MANN: Then if you don't introduce two types of pions, etc., these peculiar protons that we don't have around here are also coupled to the same pions, and at Berkeley they should make both kinds. Half of the anti-proton beam should consist of alien particles incapable of annihilating ordinary matter, which is something that can be tested. The annihilation cross sections will then be worse by a new factor of two.

M. GOLDHABER: This is already tested because the anti-protons seen in Berkeley have been followed to the end and they all annihilate. The others would look like proton contamination which is supposed to be only a few percent, certainly not 50%.

LEE: It all depends on two assumptions. First, when we start to double up particles, the end depends on experimental circumstance. To assume that the conjecture in my talk is final may be very far from the truth.

GELL-MANN: Then you might go to a proposal which doubles the pion also?

LEE: We have evidence that these particles are not produced at Berkeley. There certainly are experts here; is this the conclusion?

CHAMBERLAIN: Take the anti-proton collaboration experiment with emulsions. 37 particles came into the emulsion; 35 made a clear annihilation at the end and 2 stopped just as if they were ordinary protons. So the fraction of the non-annihilating variety might be as great as 2 in 37. These could also be positive protons, but I personally believe that they are ordinary anti-protons making stars with no visible prongs.

LEE: Let me state the second assumption. The peculiar kind of anti-protons would be made from ordinary P-P collisions or from nuclei consisting of the predominant kind of nucleons. Whether this would give precisely the same cross section is not clear.

GARWIN: Lederman and I and a group at Columbia are doing an experiment which may bear on the doubling of pions. We are looking for a preponderance of right or left-handed gamma rays emitted in the decay of the π^0 . Even though the spin of the π^0 is zero, it may still decay entirely into right or left-handed gamma rays if its structure isn't simple. So far we have no results. We have had two hours of running time which were a complete fiasco.

YANG: Let's hope that next year's conference will not be entirely preoccupied with two kinds of pions.

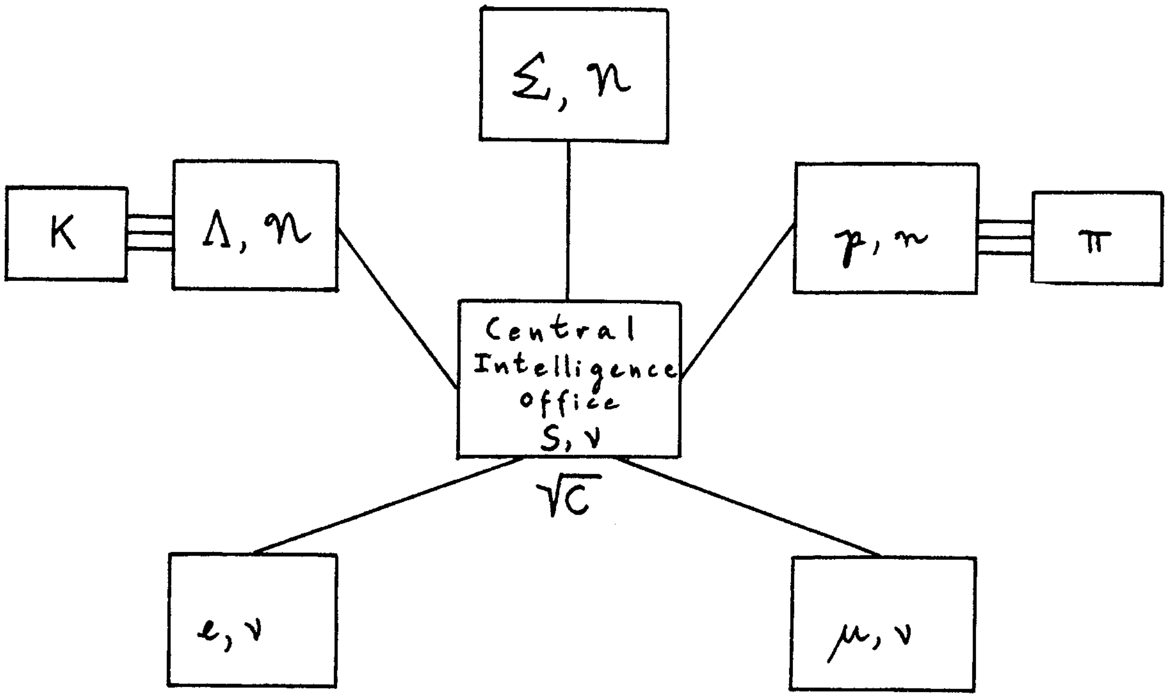
PRIMAKOFF: Let me comment about that third leg of the triangle, the muon capture process. I think one can already say on the basis of the available evidence that the G.T. part of that interaction is of the same order as in beta decay, but it still may be either tensor or axial vector. The Fermi part is also of the same order as in beta decay. This, I think, would make the angular distribution of the recoil neutrons from μ^- capture even more interesting to observe. If the interaction is indeed a linear combination of say, vector and axial vector, or scalar and tensor as it is in beta decay, then the coefficient of $\cos\theta$ for capture by hydrogen will depend on whether the coupling constants are, for example, in phase or 90° out of phase. So the experiment would also throw light on time reversal invariance in muon capture.

OPPENHEIMER: I should like to comment on just one point. The question of invariance under time reversal is by no means settled, and we all feel that the experiments will have momentous import. It is not quite right to say that a possible difference between past and future tells us something about the meaningfulness of coordinate systems, because we tend to interpret all the asymmetries in our world as historical accidents. The observed facts that our protons happen to be positive and that our hearts happen to be on the left side are elements of history not contained in the laws of physics. Cosmogony is also a form of history, and if the course from the past to the future differs inherently from the course from the future to the past, this may have nothing to do with the naming of coordinate systems; it could have to do with an often suspected, but by no means understood, relation between the very weak interactions and geometry in the large. This is in distinction to the case of a difference between right and left-handed coordinate systems. By next year this problem will probably be settled. I do not think that such desperate efforts to preserve Mach's Principle as Prof. Lee has suggested may in the end work at all.

MARSHAK: I would like to ask Prof. Lee to say a few more words about the $\tau-\theta$ puzzle. It seems that the question which started the whole business is still very much up in the air. Apparently any attempt to understand $\tau-\theta$ in terms of some Universal Fermi Interaction involving all kinds of fermions, and to infer that the $\tau-\theta$ decays into 2π or 3π because parity is not conserved in the Universal Fermi Interaction involving intermediate states with nucleons and hyperons, etc., doesn't work. Is this correct? Would you say that the Universal Fermi Interaction approach will not explain the $\tau-\theta$ puzzle even if you enlarge it to include other types of fermions besides leptons?

LEE: The considerations I shall mention, by Prof. Yang and myself, are extremely speculative and almost certainly incorrect. If we incorporate further links involving say (Λ, n)

or (Σ, n) together with K into the triangle diagram, then we obtain links not involving neutrinos. The only way we can explain parity non-conservation in these cases is through ad hoc hypotheses. The following speculation also is an ad hoc hypothesis and may not be an improvement at all. The observed weak interactions are perhaps manifestations of some other universal interaction with a different type of coupling. To illustrate, let me cut the links in the triangle, and let me join all the particle states (including strange particles) to a central intelligence office through which all reactions must proceed:



The postulated universal coupling to the central intelligence office involves two "leptons", S and ν . Particle S is an extremely heavy fermion, and ν is massless and may be identified with the neutrino. The coupling constant is the square root of the usual one. Since S is heavy, the central state is attained only in virtual processes. Violation of parity of course is due to the coupling to the central fermions S and ν .

FOLDY: Perhaps one should not place too much reliance on the TCP theorem because it contains in an essential way the assumption that the fields transform locally under all transformations. It is easy to construct simple theories that are invariant, say, under T and P but not under C. Wigner's irreducible representations of the inhomogeneous Lorentz group have this property.

LEE: This is true. But even though there is no proof for the theorem there at least exists some evidence in its favor. We know that Lorentz invariance is experimentally found to give a good account of the time dilatation effect in the decay of the muon. On the other hand we know that charge conjugation is not conserved in pion decay, and that the lifetimes of π^+ and π^- are remarkably similar. This can be explained on the basis of the TCP theorem, and any alternative possibility must meet this as a test.

FELD: I shall comment briefly on Prof. Lee's remarks upon the usefulness of observing the possible asymmetry in polarized Λ^0 decay. It is probably even more useful and more instructive if one does the same experiment on polarized Σ 's, because here we have three separate decay modes involving two isotopic spin states of the pion-nucleon system. So there is the possibility of separating out the asymmetry effect which may arise from parity non-conservation in the two isotopic spin modes. In addition we have much information about the pion-nucleon system, i.e. we know the phase shifts resulting from the interactions themselves. Knowing the polarization of the spin 1/2 Σ , we have the possibility of separating out that part of the asymmetry which comes from violation of charge conjugation, and that part which comes from violation of time reversal. These experiments then would provide almost the maximum amount of information to be obtained from a weak interaction not involving neutrinos.

FRAUENFELDER: Polarization of beta rays from unoriented nuclei.

(Editor's note: The substance of this talk together with some experimental results was published in Phys. Rev. 106, 386(1957). For this reason the talk is not reproduced at the author's request.)

M. GOLDHABER: Polarization of bremsstrahlung from beta decay.

We have just heard that negative electrons emitted by the beta source are longitudinally polarized in the backward direction. We thought it would be interesting to see whether this spirality is inherited by the bremsstrahlung produced by the electron. The experiment was performed by Grodzins, Sunyar, and myself and is simple to do once you have a method of analysing the circular polarization of the photons. The method, which was written up in detail a few years ago by Gunst and Page, consists of using the

Compton effect, which has a spin-dependent part in its cross section, as an analyser.

Fig. 1 is taken from the paper of Gunst and Page, and shows the spin-dependent part σ_1 of the cross section for photon and electron spins parallel. The units are in $2\pi r_0^2$, where r_0 is the classical electron radius. Unfortunately one does not have available at present a collection of analyzing electrons with spins all pointing in one direction. The next best thing to do is shown in Fig. 2, which is a drawing of our apparatus.

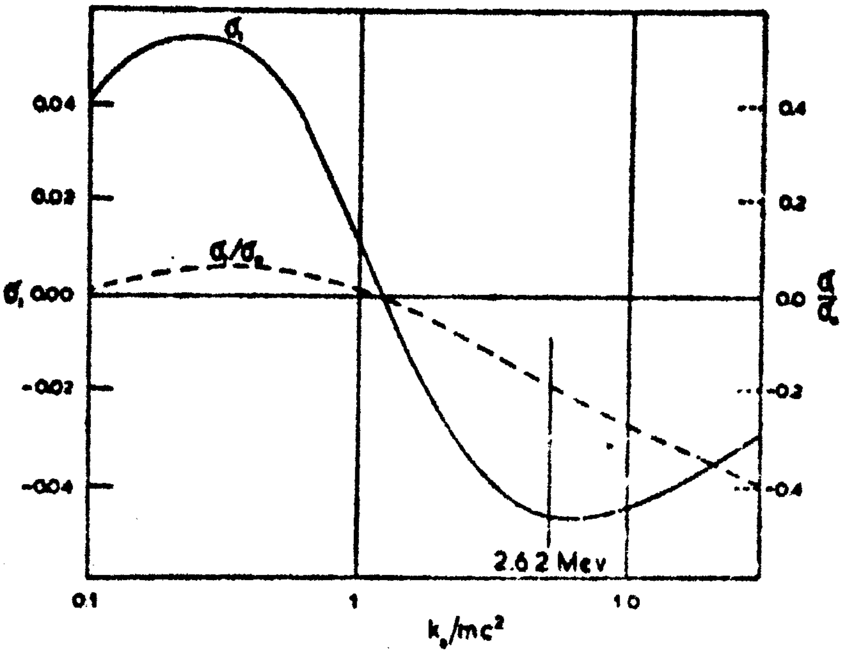


Fig. 1

The magnet polarized 2 out of the 26 electrons of each iron atom at saturation. As a beta source we chose $Sr^{90} + Y^{90}$ because this source emits no nuclear gamma rays to disturb the experiment. The lucite stopped the softer betas coming through the monel. The

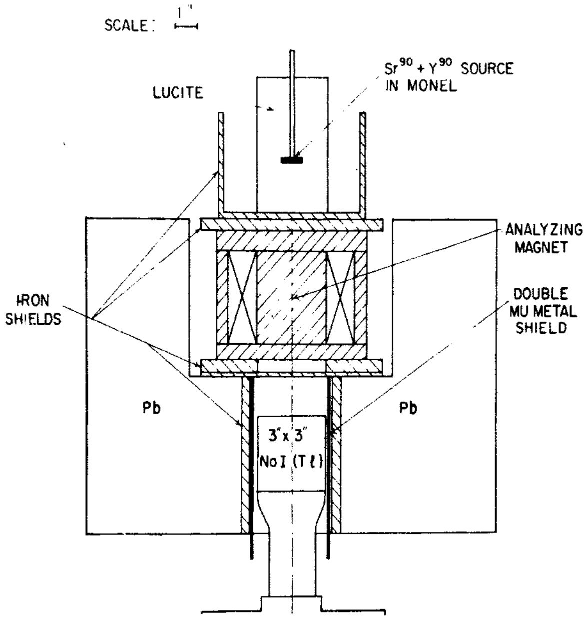


Fig. 2

bremsstrahlung photons originating in the monel are detected by the NaI crystal.

Fig. 3 shows the photon spectrum as seen through 5 inches of iron, the computed magnet response for 100% circularly polarized photons, and the experimental points. The ordinate for the latter plot is the difference in the counting rates with the field down and the field up divided by the mean counting rate. The computed curve only assumes the theoretical cross sections of Fig. 1. The experimental points at the high energy end come very close to complete polarization, and we calculate approximately 90% polarization for this region.

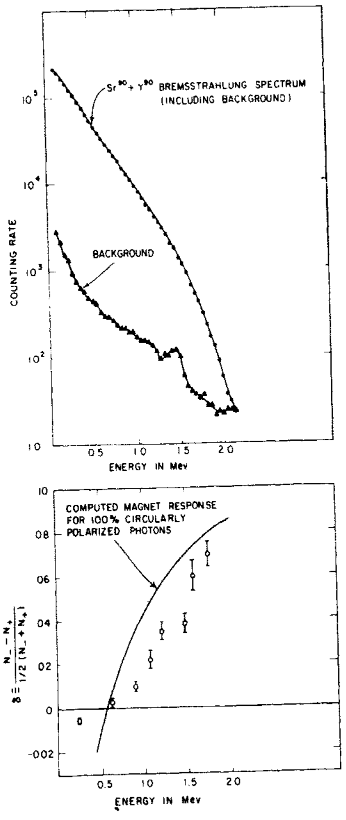


Fig. 3

By gentlemen's agreement I devote the last minute to a theory of McVoy and Dyson.

Fig. 4 shows McVoy's calculated circular polarization expected for forward bremsstrahlung from 2 Mev electrons with right-handed spirality.

Dyson has asked me to write down a formula which he has derived for the following situation. Suppose that the incident electron

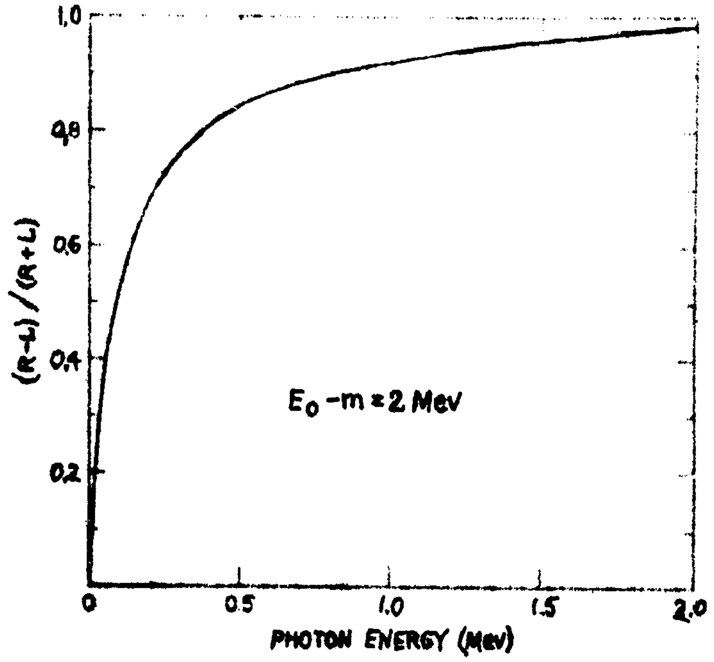


Fig. 4

is right-handedly polarized. Let σ_{RR} be the cross section for producing right-circularly polarized bremsstrahlung with the electron remaining right-handed, σ_{RL} the corresponding cross section for a right-handed photon and a left-handed electron, σ_{LR} the cross section for a left-handed photon and right-handed electron, and σ_{LL} the cross section for having the final photon and electron both left-handed. Then, for relativistic energies,

$$\sigma_{RR} : \sigma_{RL} : \sigma_{LR} : \sigma_{LL} = 2E_0^2 : k^2 : 2E^2 : 0,$$

where E_0 is the initial electron energy, k the energy of the photon, and E the final electron energy. There is a tendency of the electron to maintain its spirality, and to impress the same spirality on the photon.

The energetic photons will create pairs. Let σ_{RR} be the cross section for producing a right-handed positron and a right-handed electron, σ_{RL} be the cross section for a right-handed positron and a left-handed electron, etc. Then Dyson gives the formula

$$\sigma_{RR} : \sigma_{RL} : \sigma_{LR} : \sigma_{LL} = k^2 : 2E_+^2 : 2E_-^2 : 0,$$

where the notation is obvious. Since k^2 is the largest of these numbers, there is a tendency to maintain the spirality of the incident photon. Thus spirality seems to be an inheritable characteristic in such chain reactions, and the high energy parts of high energy showers should keep on adding spin in the same direction.

WU: Beta decay experiments and non-conservation of parity.

The questions raised by the τ- θ puzzle gave the subject of beta decay an opportunity to render valuable service in verifying non-conservation of parity and charge conjugation in weak interactions. Beta decay data also revealed for the first time the possibility of applying the two-component theory of the neutrino to beta interactions.

In our first experiment at Columbia and the National Bureau of Standards we investigated the asymmetry of the beta distribution from polarized Co^{60} nuclei, because the transition is of pure G.T. type ($5^+ \longrightarrow 4^+$). We saw a pronounced negative asymmetry with respect to the direction of spin alignment. If θ is the angle between the nuclear polarization $\langle J_z \rangle$ and the direction of emission of the electron, we may write the angular distribution in the form

$$I(\theta) = \xi\left[1 + \alpha \cos\theta\right]$$

where

$$\xi = |M_{GT}|^2\left[|C_T|^2 + |C'_T|^2 + |C_A|^2 + |C'_A|^2\right]$$

$$\alpha = \frac{1}{J}\langle J_z\rangle \frac{v}{c} A$$

$$A\xi = |M_{GT}|^2\Big[2\,\mathrm{Re}\left(C_T C'^*_T - C_A C'^*_A\right) - (Z\alpha m/p)\,2\,\mathrm{Im}\left(C_T C'^*_A + C'_T C^*_A\right)\Big],$$

and the second term in $A\xi$ is the Coulomb correction. With $v/c \sim .65$, and the amount of polarization (calculated from the anisotropy of the γ rays) of order 60%, we observed an asymmetry ratio α of about -0.40. Therefore A is of order unity. From this we draw two conclusions:

First, we may place an upper limit on the contribution from the Z -dependent Coulomb part, using the data supplied by the $\beta - \nu$ angular correlation in the decay of He^6 . Since $Z = 28$, $\alpha = 1/137$, and the He^6 data indicates that the remaining factor is less than $2/\sqrt{3}$, the Z -dependent term is less than 0.23. Therefore most of the asymmetry is provided by the first term. But such a term exists only if neither charge conjugation nor parity are conserved, so the experiment already demonstrates the non-invariance of C and P.

Secondly, since A $\sim$ 1 and the asymmetry ratio was observed to be negative, we infer that in this case $C_T = - C'_T$. According to Lee and Yang this indicates that in the beta decay of the neutron an anti-neutrino comes out.

The second term will only exist if there is non-invariance with respect to parity and time reversal. Unfortunately, as I said, the maximum contribution will be only about 20%, but it is nice to see whether we can isolate the part of the asymmetry due to this momentum-dependent term. As I'll show later, the observed asymmetry is practically proportional to v/c and thus is furnished by the first term. There is practically no effect from the second term. But one cannot draw conclusions about invariance properties from the absence of this effect because this Z -dependent term is small at best, and it is also possible that the axial vector part of the interaction is equal to zero or very small compared to the tensor part. Therefore this method, although suggested as one of the ways of testing time reversal invariance, is of limited usefulness.

Next we investigated Co^{58} because it is a positron emitter and the transition is $2^+ \longrightarrow 2^+$, which means that we now have an admixture of Gamow-Teller and Fermi interactions. With the amount of nuclear polarization and the value of v/c the same as in the Co^{60} case, we obtained an asymmetry ratio one-third of that for Co^{60}, with positive sign ($\alpha > 0$). At first glance this appears to be a very satisfactory result, because for a J $\longrightarrow$ J transition the I(θ) expression carries an extra factor of $\frac{1}{J+1}$,

so that the Co^{58} asymmetry ratio should indeed be 1/3 of the Co^{60} ratio, and the signs should be opposite since Co^{58} is a positron emitter. But this argument is based on the assumption that the decay proceeds through a pure Gamow-Teller interaction (and, of course, we again neglect the Coulomb term). However, if the Fermi matrix element M_F does not vanish or is not small, then we must consider the interference between the Gamow-Teller and Fermi interactions. This interference adds a term

$$|M_F||M_{GT}|\sqrt{\frac{J}{J+1}}\ 2\,\mathrm{Re}\left[C_S C_T'^{*} + C_S' C_T^{*}\right]$$

to the expression for the asymmetry ratio, where for the moment we neglect vector interactions. Griffin and Murray, studying the anisotropy of the γ rays that follow the beta decay, have determined the ratio $|M_F|^2/|M_{GT}|^2$ to be equal to about 1/8. Unfortunately, the interference term involves the absolute values, not the squares, of the matrix elements, and therefore is of the same order of magnitude as the first term. The numerical value of the interference term, relative to the first term, is $\sqrt{3}$ if the scalar and tensor interactions have opposite sign, and $-\sqrt{3}$ if they have the same sign. In the first case the asymmetry ratio has the correct sign, but its value is much larger than the observed value; in the second case the sign would be wrong. The observed asymmetry ratio is well given by the first term alone, a result confirmed by the Leyden group who also investigated Co^{58}

There are several possible reasons for this discrepancy. One is that the determination of $|M_F|^2/|M_{GT}|^2$ may be off by a large enough factor. Another is that we have neglected the vector interactions in computing the interference term, which more rigorously should read

$$|M_F||M_{GT}|\sqrt{J/J+1}\ 2\,\mathcal{R}e\left[C_S C_T'^{*} + C_S' C_T^{*} - C_V C_A'^{*} - C_V' C_A^{*}\right].$$

The evidence on the relative strengths of scalar and vector components in the Fermi interaction is no longer so convincing as we previously had thought, because we don't know if time reversal invariance holds true. The old methods used beta-neutrino angular correlations to determine the nature of the interactions. For example He^6 , which decays through a pure G.T. interaction, was used to show that this interaction is mostly tensor. Ne^{19} was used to investigate the Fermi interaction, but since here a mixture of Fermi and G.T. interactions is involved, this method turned out to be not very sensitive. The decay of A^{35} would furnish a much more sensitive test, because here $|M_{GT}|^2/|M_F|^2 = 1/20$ Knowledge about the exact nature of the Fermi interaction, i.e. the relative strength of C_S and C_V, becomes essential when we wish to select the best experimental method of testing time reversal invariance.

Nowadays we no longer need to use the beta-neutrino angular correlation method, which is difficult and insensitive. As Prof. Lee has pointed out, the longitudinal polarization of electrons from scalar, pseudo-scalar, and tensor interactions is different from the longitudinal polarization of electrons coming out of vector and axial vector interactions. Therefore it would be most interesting to investigate the longitudinal polarization of electrons coming from pure Fermi decays, i.e. $0 \longrightarrow 0$ transitions, of which there are many. There are three methods of measuring the polarization ; two of them have been discussed today. One method employs Mott scattering (see Frauenfelder), the second method uses the circular polarization of the forward bremsstrahlung (see Goldhaber), and the third is the ingenious method of Page and Heinberg who use the Doppler effect in positronium. Mott scattering is very good in the energy range of 50 to 500 Kev, but at higher energies it becomes very difficult to convert longitudinal into transverse polarization. The bremsstrahlung technique should be very good at high energies. It should also work for positrons because, as Prof. Dyson assures me, the annihilation radiation in the forward direction should be nearly 100% polarized.

Now let me bring you up to date on the experimental results.

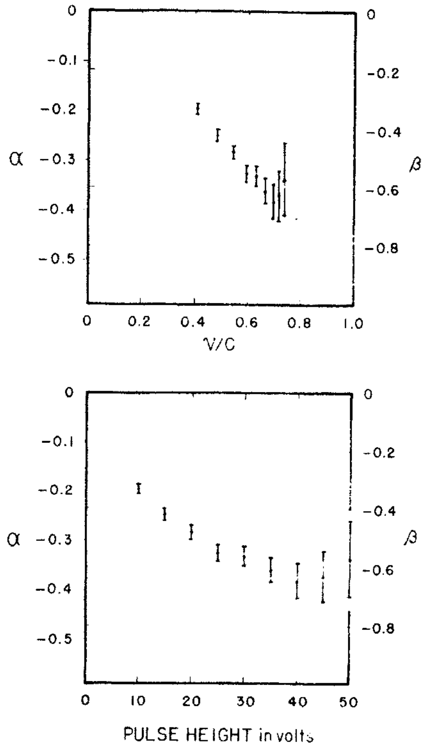


Fig. 5

Fig. 5 shows the experimental asymmetry coefficient α and the asymmetry parameter β of electrons from Co^{60} nuclei as a function of pulse height and v/c. β is proportional to v/c, and the momentum-independent term is small, since the curve passes practically through the origin.

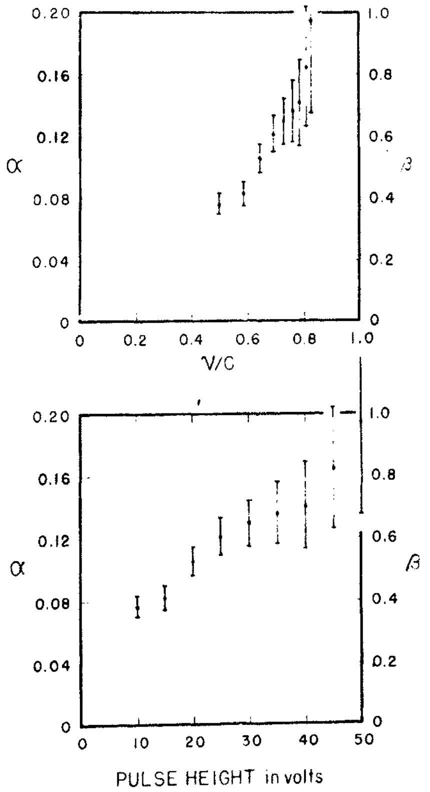


Fig. 6

Fig. 6 presents similar data for the positrons from Co^{58}. β again is nearly proportional to v/c in accordance with a pure G.T. transition. The interference term with the Fermi interaction seems to be absent; β has been deduced assuming that the total contribution to the asymmetry comes from the G. T. interaction alone.

ASYMMETRY OF β - DISTRIBUTION FROM POLARIZED NUCLEI

METHOD	MAGNETIC h.f.s. METHOD AND β - DETECTOR	MAGNETIC h.f.s. METHOD AND β - DETECTOR	MAGNETIC h.f.s. METHOD AND ANNIHILATION RADIATION	$\beta - \gamma$ (CIRCULARLY POLARIZED) COINCIDENCE	$\beta - \gamma$ (CIRCULARLY POLARIZED) COINCIDENCE
RADIOACTIVE NUCLEI	Co^{60} β^- $5^+ \rightarrow 4^+$	Co^{58} β^+ $2^+ \longrightarrow 2^+$	Co^{58} β^+ $2^+ \longrightarrow 2^+$	Co^{60} β^- $5^+ \longrightarrow 4^+$ Na^{22} β^+ $3^+ \longrightarrow 2^+$	Co^{60} β^- $5^+ \xrightarrow{\beta^-} 4^+ \xrightarrow{\gamma_1} 2^+ \xrightarrow{\gamma_2} 0^+$ Au^{198} β^- $3^- \xrightarrow{\beta^-} 2^+ \xrightarrow{\gamma} 0^+$ Hg^{203} β^- $5/2^- \xrightarrow{\beta^-} 3/2^+ \xrightarrow{\gamma}$
α OBSERVED	POLARIZATION $\frac{\langle J_z \rangle}{J} \sim 60\%$ $\frac{v}{c} = 0.6$ $\alpha = -0.4$	POLARIZATION $\frac{\langle J_z \rangle}{J} \sim 60\%$ $\frac{v}{c} = 0.6$ $\alpha = +0.11$	POLARIZATION $\frac{\langle J_z \rangle}{J} \sim 35\%$ $\langle \frac{v}{c} \rangle \sim 0.75$ $\alpha \sim +0.06$	$E = \frac{2(R_1 - R_2)}{R_1 + R_2}$ $E = 2fP \left\| \frac{\sigma_p}{\sigma_0} \right\|$ $P = \alpha(\frac{v}{c}) \cos \theta$ Co^{60}: -0.41 ± 0.07 Na^{22}: $+0.39 \pm 0.08$	Co^{60} α : -0.41 ± 0.09 Au^{198} α: $+0.44 \pm 0.13$ Hg^{203} α: + (SMALL)
AUTHORS	C.S. WU E. AMBLER R.W. HAYWARD D.D. HOPPES R.P. HUDSON	C.S. WU E. AMBLER R.W. HAYWARD D.D. HOPPES R.P. HUDSON	H. POSTMA W.J. HUISKAMP A.R. MIEDEMA J.J. STEENLAND H.A. TOLHOEK C.J. GORTER	H. SCHOPPER	FELIX BOEHM A.H. WAPSTRA

Fig. 7

Fig. 7 summarizes the results of measurements of the asymmetry of beta distributions from polarized nuclei.

LONGITUDINAL POLARIZATION OF BETA-PARTICLES

METHODS	MOTT SCATTERING ELECTRIC FIELD	MOTT SCATTERING CROSS E AND H FIELD	MOTT SCATTERING CROSS E AND H FIELD	DOPPLER EFFECT IN POSITRONIUM	DETECTION OF CIRCULAR POLARIZATION OF THE FORWARD BREMSSTRAHLUNG	DETECTION OF CIRCULAR POLARIZATION OF THE FORWARD BREMSSTRAHLUNG
RADIOACTIVE NUCLEI	Co^{60} $5^+ \xrightarrow{\beta^-} 4^+$	Co^{60} $5^+ \xrightarrow{\beta^-} 4^+$	$Sr^{90} + Y^{90}$	Na^{22} $3^+ \xrightarrow{\beta^+} 2^+$	$Sr^{90} + Y^{90}$ IN EQUILIBRIUM $2^- \xrightarrow{\beta^-} 0^+$	Tm^{170} $1^- \xrightarrow{\beta^-} 0^+$
LONGITUDINAL POLARIZATION P	$P = -0.40$ for $\frac{v}{c} = 0.49 \pm 20\%$	$P = -0.60 \pm 0.13$ for $\frac{v}{c} = 0.60$	LONGITUDINAL POLARIZATION IS IN GOOD AGREEMENT WITH THE PREDICTION OF $\frac{v}{c}$	$P = +0.4 \langle \frac{v}{c} \rangle$ NO CORRECTIONS WERE APPLIED	NEAR THE HIGH ENERGY END THE PHOTONS ARE ALMOST COMPLETELY CIRULARLY POLARIZED AND ANTI-PARALLEL TO THEIR DIRECTION OF PROPAGATION	$P = (-.86 \pm .14) \frac{v}{c}$
AUTHORS	H. FRAUENFELDER R. BOBONE E. von GOELER N. LEVINE H.R. LEWIS R.N. PEACOCK A. ROSSI G. De PASQUALI	P.E. CAVANAGH TURNER COLEMAN GARD RIDLEY	A.I. ALIKHANOV G.P. YELISEYEV V.A. LIUBIMOV B.V. ERSHLER	L.A. PAGE M. HEINBERG	M. GOLDHABER L. GRODZINS A.W. SUNYAR	FELIX BOEHM A.H. WAPSTRA

Fig. 8

Fig. 8 summarizes the results of measurements of the longitudinal polarization of beta particles.

All these results are in general agreement with the two-component theory of the neutrino.

DISCUSSION

BREIT: I shall comment on the question of Mach's Principle raised in Prof. Lee's introductory talk. The situation is essentially different depending on whether one deals with a linear or a non-linear theory. All the present theories are linear, but do not really make complete sense. If between the fundamental theory and its application to experiment such as beta decay there is an essential non-linearity, then one can also expect an instability. A simple example of instability is furnished by an ordinary vacuum tube, which has states with hysteresis. For the same plate voltage, there may either be oscillations or no oscillations. In this connection it would seem that right-handedness or left-handedness might not be essential properties of the system as a whole. A slight presence of a right-handed element some place in the system could induce a right-handedness throughout its entirety, and a general circulation of matter as a whole could in principle induce a right-handedness in the neutrino which would no longer be a simple element but would be composed, in a sense, of other particles. Perhaps this is a little too general, but some recognition of the difference between linear and non-linear theories might clarify this puzzling business of right and left-handedness.

BARKAS: Electron spectrum from muon decay:

Dr. Dudziak has given me some information to present, as shown in Fig. 9. The data were presented last year, but as you know, the first information was disqualified because of a saturation effect discovered in the analyzing magnet. Much work has been done since, and the new data on the limits of the spectral parameter η as a function of the Michel parameter ρ is presented in Fig. 9. Including Finkelstein's radiative correction which is about .04, the best value of ρ quoted by Dudziak and Sagane is .72 ± .05.

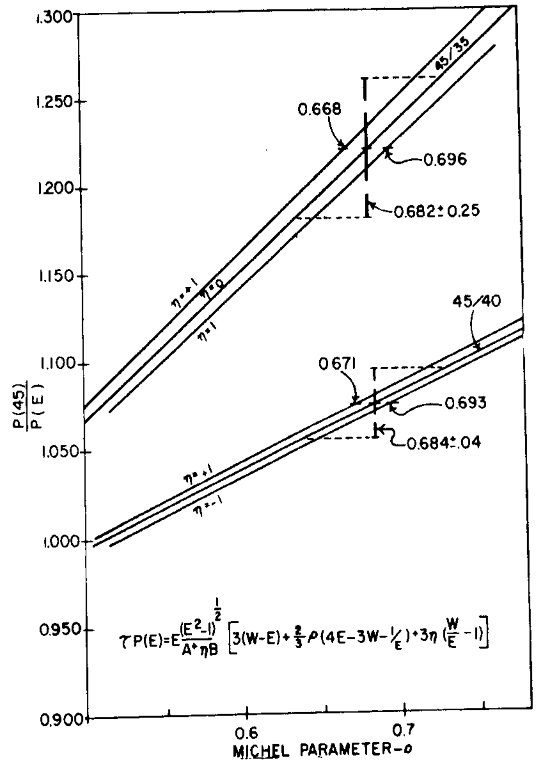


Fig. 9

PLESS: Polarized muon decay.

This work is a joint effort of the MIT-Harvard bubble chamber group and the bubble chamber group of the University of Chicago where the exposures were made. The people involved are shown in Table 1.

Table 1

M.I.T.	Harvard	Chicago
Brenner	Milburn	Bizzarri
Pless	Ramsey	Hildebrand
Williams	Shapiro	
	Strauch	
	Street	
	Young	

The purpose of the experiment is to investigate the energy dependence of the asymmetry in $\mu - e$ decay. Positive pions were stopped in a propane bubble chamber, the resulting $\mu - e$ angular distribution was measured, and the results were compared with the Lee-Yang theory. The latter predicts an energy dependence of the distribution of form

$$dN = 2x^2\left[(3-2x) + \xi \cos\theta\,(1-2x)\right] dx$$

where $x = \frac{E}{E_{max}}$. According to the present data, $\xi = 1$.

Integrating this expression from 0 to some value K, we obtain the angular distribution for all electrons whose energy is less than KE_{max}:

$$\int_0^K dN = C(K)\left[1 + \alpha(K)\cos\theta\right]$$

α is the asymmetry ratio and C is a constant. Our results are summarized in Table 2.

Table 2

K	α Lee-Yang	α Kinoshita (Rad. Corr.)	α 45% Depol.	α Measured
1	-.33	-.33		-.18 ± .05 (1188 events)
.2(E=10 Mev)	+.257	+.205	+.11	-.03 ± .1 (376 events)

The third column lists the values of α including the Kinoshita-Sirlin radiative correction. The measured value for K = 1 indicates a 45% depolarization, and this has been used to calculate the value for K = .2 in the fourth column. The statistics permits us only to say that the asymmetry tends to decrease for the lower energy events. We have not yet actually seen a reversal in sign of α.

SKINNER: Polarized muon decay.

I shall report on work done by M. H. Alston, W. H. Evans,

R. W. Newport, and P. R. Williams, who stopped the π^+ beam from the Liverpool cyclotron in a propane bubble chamber 3 inches in diameter and 6 inches long. We analyzed 3500 π-μ-e decays and obtained $\alpha = -0.19 \pm 0.04$, in very good agreement with the results reported by the previous speaker. Our results are shown in Fig. 10.

We discarded the two extreme points at large and small angles because there was evidence that tracks were missed. The large deviations from the straight line are probably not outside statistical errors.

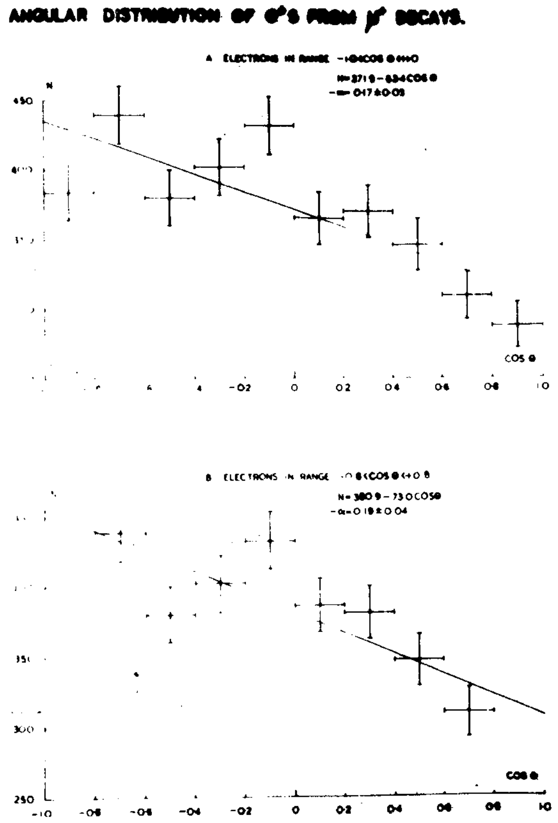


Fig. 10

<u>LEDERMAN</u>: Polarized muon decay and the magnetic moment of the muon.

I shall first report on work done at Columbia by Garwin, Coffin, Berley, Weinrich, and myself. Using the precession of muons in a magnetic field we investigated the asymmetry in the decay electron distribution as a function of energy. Fig. 11 shows a typical curve obtained in the beautiful experiment of Cassels and coworkers at Liverpool.

The time discrimination was made with a multi-channel time analyser, and the field was large enough so that the muons precessed many times during the 4 μsec observation time. This precise technique was first employed by Telegdi, Wright and co-workers at Chicago.

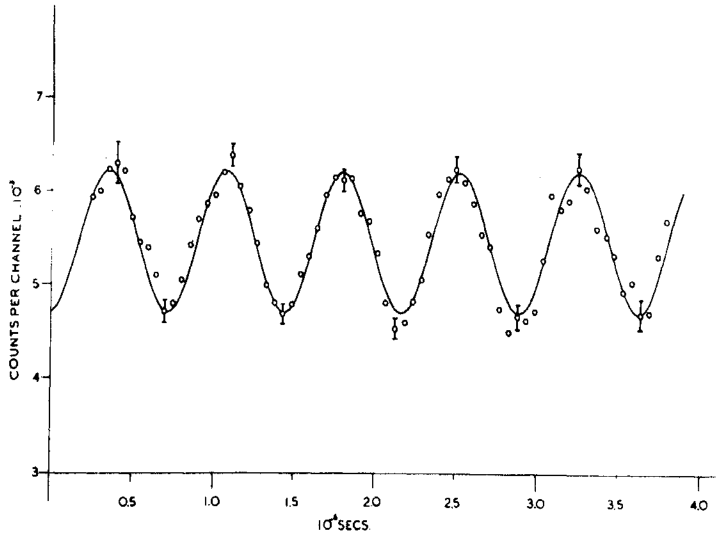


Fig. 11

In our experiments we used values of time and magnetic field appropriate for measuring peak to valley ratios, and varied the energy of the observed electrons by changing the range requirements for their detection, using carbon absorbers. The results are shown in Fig. 12.

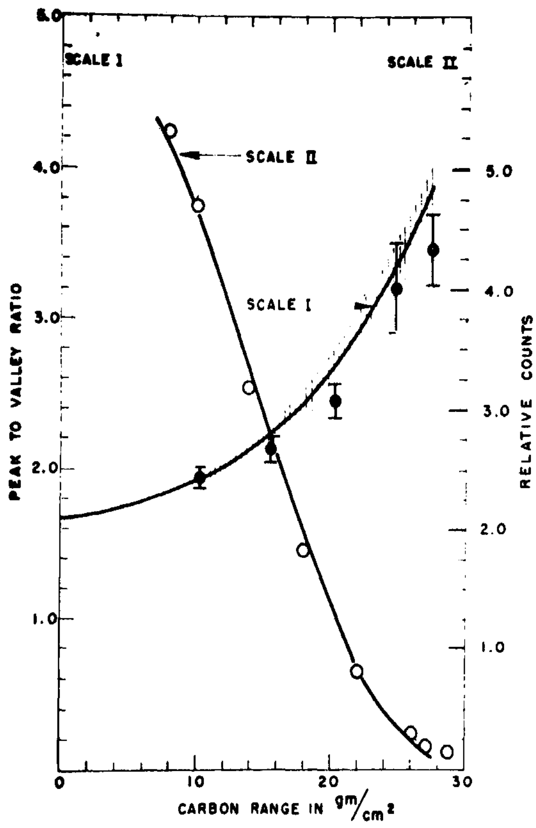


Fig. 12

The open circles give a calibration curve obtained from the electron spectrum of unpolarized muons. The experimental points agree well with the prediction of the two-component theory which is shown by the solid line, especially if the theoretical curve is smeared a bit due to uncertainties in the resolution function.

The data was also compared to the predictions of the four-component theory as calculated by Lubkin, Larsen, and Tausner. They find a distribution of form

$$f(x,\theta) = Ax^2 dx \left\{(1-x) + \frac{2}{9}\rho(4x-3) + \cos\theta\left[\alpha(1-x) + \frac{2}{9}\xi(4x-3)\right]\right\},$$

where ρ is the Michel parameter, and α and ξ are functions of the ten coupling constants. Using the best value of ρ including the radiative corrections, we obtain $\frac{\alpha}{\xi} = \frac{5 \pm 0.3}{9}$ The two-component theory gives $\frac{\alpha}{\xi} = \frac{4}{9}$, and the discrepancy may possibly be blamed on the energy resolution function or it may perhaps indicate a real (small) deviation from the two-component theory prediction.

The angular distribution integrated over energies has the form $1 + \alpha\cos\theta$, $\alpha = 1/3\, \xi B$, where ξ is essentially the ratio of the parity conserving to the parity non-conserving coupling constant, and **B** is the percentage polarization of the muon beam. For α in graphite we obtain the values

$\alpha =$ -.25 ± .02 (Present work)

$\alpha =$ -.24 ± .02 (Liverpool group)

$\alpha =$ -.24 ± .02 (Chicago)

The above close agreement indicates that the muon beams are nearly 100% polarized, and therefore we get $\xi \cong$ 0.8 rather than 1.

Secondly I shall mention the molecular beam type resonance experiment on the magnetic moment of the muon, done by Garwin, Sachs, Penman, Coffin, and myself at Columbia. Fig. 13 shows the experimental results obtained with an R.F. frequency of 16 mc.

The target material was bromoform, and we get

$$g_\mu = 2.0064 \pm .0048.$$

The value predicted by quantum electrodynamics, including the second order radiative correction, is 2.002. It is interesting that there is as yet no indication of an anomalously anomalous moment. If such an effect were found, one might question the mass of the muon which is known to 1 part in 2000. But Rainwater's mesic X-ray data set a limit to the lowest permissible value of the muon mass, and from this it follows that $g_\mu \geq 2.0044 \pm .0048$.

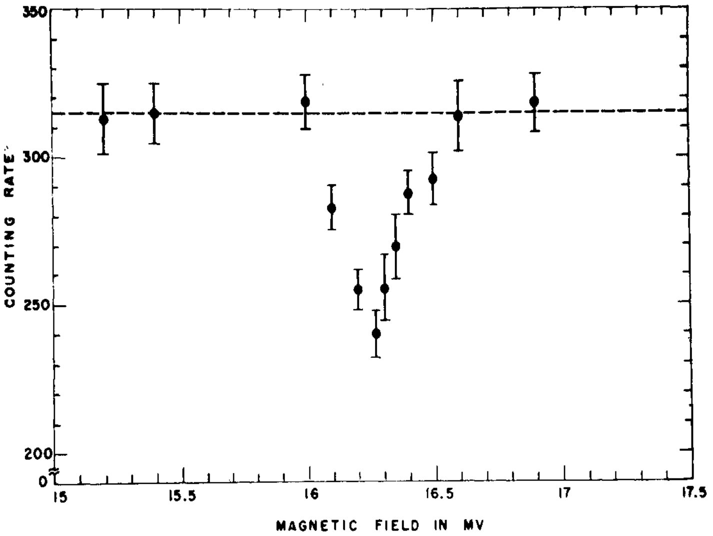


Fig. 13

Finally, we are repeating Goldhaber's experiment on the circular polarization of bremsstrahlung, using decay positrons from μ^+ This would throw light on the question of conservation of leptons, as discussed by Prof. Lee. We find, for the ratio of counting rate with the magnet one way to that with the magnet reversed, a value of 1.06 ± 0.09. Conservation of leptons should give ~ 0.95, and we think that there is a 5% effect. This is just a status report and we are continuing this experiment. (Addendum: Lederman has submitted a more recent result of 0.95 ± 0.02.)

S. C. WRIGHT: Polarized muon decay, muonium formation, and depolarization effects.

This is a report on counter experiments with polarized muons done at Chicago. Campbell, E. L. Garwin, Miller, Sens, Swanson, Telegdi, Yovanovitch and myself participated in this work. The angular distribution $W(\theta) = 1 - a \cos\theta$ of the decay electrons (+, -) from μ 's stopped in a target leads to a counting rate

$$W(B,t) = 1 - a \cos (cBt + \varphi) e^{-\lambda t}; \quad \frac{W(\uparrow) - W(\downarrow)}{W(\uparrow) + W(\downarrow)} = a \sin (cBt)$$

where B is the field which we keep fixed; φ is the starting phase determined by the electron counter position.

W(B,t) was displayed on a 100-channel pulseheight analyzer connected to a delay-to-pulseheight converter fed by a μ start- and an e stop-pulse; this converter covered a time interval of 2.7 μsec. Some first results obtained by us by this method were presented at the 1957 N.Y. Meeting. Fig. 14 shows a typical precession curve (μ^+ in graphite). A summary of results for μ^+ in various materials is shown in Table 3. All indicated values of -a are to be compared with graphite, where -a = -.24. Errors are ± 0.01.

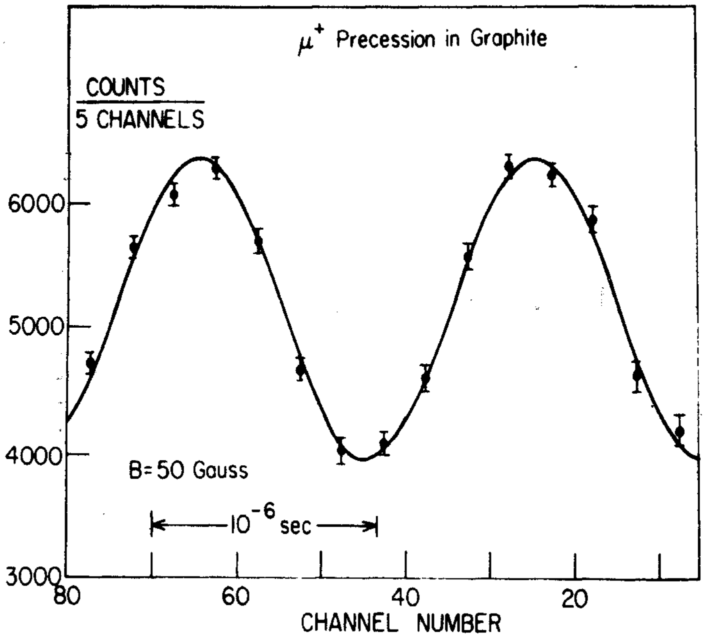


Fig. 14

The materials tested for depolarization included several undeveloped emulsion samples. The sample of the batch in which the Minnesota balloon experiment yielded no asymmetry behaved normally. Though "a" is seen to vary widely over different types of material, we do in general not observe any decay (relaxation) of the spin precession. This indicates that in general the depolarizing mechanism must act rapidly in the last stages of the slowing down process and then stop. Only in the case of boron carbide did we find a slow but observable decay of the asymmetry.

Table 3

ASYMMETRY VALUES FOR DECAY OF POSITIVE MUONS

TARGET	a
Graphite 1	.23
Graphite 2	.23
Graphite 3	.24
Graphite 4	.24
Amorphous Carbon	.25
Diamond	.04
Nuclear Emulsion 1	.10
Nuclear Emulsion 2	.10
Nuclear Emulsion 3	.11
Nuclear Emulsion 4	.12±.03
Lithium	.21
Beryllium	.23
Magnesium	.26
Aluminum	.24
Boron Carbide	.23
Silicon Carbide	.24
Aluminum Oxide	.00
Magnesium Oxide	.09
Fused Quartz	.04
Vitreosil	.01
Sodium Chloride	.04
Caesium Iodide	.00
Magnesium Fluoride	.18
Phosphorous (red)	.00
Sulphur	.00

ASYMMETRY VALUES FOR DECAY OF POSITIVE MUONS

TARGET	a
Dow Corning 200 Fluid	.13
Benzene	.02
Chloroform	.21
Phenylcyclohexane	.09
Polystyrene	.06
Polyethylene	.16
Teflon	.18±.03
Propane	.17±.02
Water	
pH 2	.16
pH 7	.17
pH 12	.16
Water-.08 M NaCl	
pH 1.2	.17
pH 2.2	.18
pH 4.4	.17
pH 5.3	.15
pH 6.1	.15
pH 6.8	.16
pH 11.0	.17
pH 11.2	.15

Some experiments were carried out with negative muons. In graphite, $a = -0.06$. Within our statistics, a high and low energy (190 and 90 Mev) muon beam yield the same asymmetry.

In a second series of experiments, we looked for coupling effects between the muon moment and either electronic or nuclear moments. For example, the muonium system ($e^- \mu^+$) would have a magnetic moment approximating that of the electron, and its gyromagnetic ratio would depend on the spin of the muon, changing by a factor of about 2 for μ-spin of 1/2 or 3/2. Similarly, the gyromagnetic ratios of various kinds of μ^--mesic atoms would also measure the spin of the muon. Here we have to distinguish two possible situations: (a) closed electron shell, (b) unpaired electrons. For (a) Li + μ^- , losing an electron, for (b) C + μ^- , losing one electron, are simple examples. So far we have not detected any of these systems but are continuing the search.

We have also done a Garwin-Lederman type experiment on μ^+ decay, replacing the electron counter by a 5-inch NaI crystal. We looked for the energy dependence of the "a" coefficient, and fitted our data with an expression of the form $x^2 \left[r(1 - x) + (2x - 1) \right]$, where x is the electron energy in dimensionless units; $r = 0$ would correspond to the 2-component theory. We obtain $r = 0.2 \pm .15$, but the χ^2 -test is not too good so that not much confidence can be attached to this result.

Finally, we have tried to detect the "Paschen-Back effect" in our counter work on depolarization. This is the same effect which Orear and co-workers are investigating by emulsion techniques. We have found that a longitudinal magnetic field increases the magnitude of "a" in emulsion by about a factor two, leaving the asymmetry in aluminum unaffected.

KAPLON: Polarized muon decay in emulsion.

I am reporting on the collaborative efforts of a large group of people. Table 4 summarizes essentially all of the emulsion work. The groups are listed by name; it would take another table to list all the individual names.

The asymmetry coefficient in emulsion can be determined from the forward-backward ratio or by doing an analysis of the angular distribution. Both methods give essentially the same results. The first set of 6 groups listed in Table 4 all used machine-produced pions. The next set of 4 used cosmic rays. In addition I've listed Harris and Orear's experiment involving the Paschen-Back effect in 9000 gauss, and the other Columbia experiment using 700 gauss.

We can use the emulsion data in two ways to get more information. For instance, by taking the ratio of the Columbia determination of the coefficient in emulsion to the Columbia determination in carbon, assuming that carbon is unquenched, we can determine the emulsion quenching factor. Alternatively, by comparing the Columbia emulsion data to the ordinary emulsion data we can determine the polarization of the Columbia beam. In either case we find about 93% polarization for the Columbia beam, and the coupling constant mixture factor ξ of about $0.8 \pm .15$.

Table 4

Group	Source	Magnetic Field (Gauss)	$-\alpha$
Chicago	Chicago	4×10^{-3}	0.174 ± 0.038
Göttingen	Chicago	4×10^{-3}	0.095 ± 0.044
Rochester	Cosmotron	1	0.19 ± 0.06
Cambridge(Eng.)	Liverpool	0.15	0.149 ± 0.033
Cambridge(Eng.)	Liverpool x2 Diluted Em.	0.15	0.19 ± 0.033
Brussels	Rochester	100	0.22 ± 0.12
Minnesota*	CR(22Liter Stack)	Earth	0.03 ± 0.04
Rome	CR(0.36 Liter Stack)	Earth	0.22 ± 0.067
Copenhagen	CR(1.4 Liter Stack)	Earth	0.17 ± 0.07
Bristol	CR(Σ several stacks)	Earth	0.08 ± 0.05

Incident μ -meson beam

Harris-Orear	Columbia	9000 along beam	0.249 ± 0.036
Pesvner	Columbia	700 along beam	0.14 ± 0.07

Counters - Incident μ-meson beam

Columbia	Columbia	variable along beam	0.14 ± 0.03 Ext. 0 En.

Various Emulsion Samples

Chicago	Chicago	Chicago I	0.10 ± 0.01
		" II	Same
		Minn. I	0.12 ± 0.04
		" II*	0.11 ± 0.01

Averages

Machine Produced - Normal G-5 Emulsion	0.150 ± 0.020
Cosmic Ray	0.090 ± 0.026
Combined - CR + Machine	0.126 ± 0.016

*Same Emulsion Batch

GOEBEL: Theoretical considerations concerning depolarization effects.

This is an attempt to make a consistent picture of the depolarization of μ^+ mesons in matter. I begin with muonium formation, which is the only effective depolarization mechanism known. Muonium, as mentioned by Dr. Wright, is the "atom" formed when the μ^+ captures an electron. As is well known, if $m_j = 0$ muonium is formed, i.e. the μ^+ with spin up captures an electron with spin down, the μ is rapidly depolarized at the rate of the hyperfine splitting frequency $\Delta\omega \simeq 3.8 \times 10^{10}$ sec^{-1}. The other 50% of the time, the spin up μ^+ captures a spin up electron to form triplet muonium. There is no "internal" depolarization of the μ in this case, but the relatively large magnetic moment of the electron is a "handle" on the spin of the μ, so that a constant field of $\sim$ 1/20 Gauss will now depolarize it, compared to the 5 Gauss needed for a bare μ. So the amount of depolarization of the μ, when the external field is small, depends on (a) the probability of the formation of muonium as the μ comes to rest; (I think this is unity in an insulator. In a metal, there is an overabundance of "free" electrons present, so that no one can be bound. Hence there is no depolarization in metals and carbon) (b) the chemical stability of the muonium; (I remark here that since $m_\mu >> m_e$, the μ^+ is equivalent to a proton for electronic phenomena such as chemistry; i.e. chemically, muonium is atomic hydrogen.) For instance, in CCl_4 the muonium (symbol M) can have the reaction $M + CCl_4 \longrightarrow CCl_3 + MCl$, so that the μ ends up in a "saturated" chemical compound in which there is (unlike in muonium) no electronic magnetic field. A question is: is the rate of such a chemical reaction rapid enough to save the μ from being depolarized in $m_j = 0$ muonium? At room temperature, apparently not: the reaction is about 100 times too slow. But there is no reason why the process shouldn't occur when the muonium is epithermal, while coming to rest. In fact, since Cassels finds the maximum asymmetry in CCl_4, we assume this to occur. In general then, we have a reason for the asymmetry to persist in any material in which atomic hydrogen can chemically combine. The precise degree of depolarization depends on the probability of a chemical reaction occuring as the muonium comes to rest.

The chemical stability of muonium in ionic crystals is a difficult theoretical problem. We won't discuss the situation, but instead refer to an experimental paper by Delbecq, Smaller and Yuster (at Argonne) who find interstitial hydrogen is stable in KCl, at least below 100° K; however, they believe that above that temperature the hydrogen disappears because it migrates around and annihilates itself into H_2 . This process does not operate for the μ case, at least at present beam intensities.

What about the triplet muonium? From the previously mentioned result on the mobility of H in KCl, one can estimate the relaxation time τ (i.e. the mean time the muonium stays in one place) and see if this is long enough for the nuclear magnetic fields ($\simeq$ 1 Gauss) to depolarize the triplet muonium. The answer is inconclusive, for τ is calculated to be only a factor of 10 too short; considering the crudity of the estimation I would not say that this contradicts the possibility of depolarization. The depolarization of the triplet muonium is, of course, required by experiments which find zero asymmetry in a field less than 4×10^{-3} Gauss.

We now must discuss photographic emulsion. If one followed the μ^- and π^- results that 70% to 80% stop in the AgBr (this is the Fermi-Teller law), one would conclude that at least 70% to 80% of μ^+ in emulsion get depolarized, which is not the case. I think the way out is to recognize that the Fermi-Teller law may break down for positive particles. In the last stage of slowing down, ordinary ionization does not occur. For a negative particle "adiabatic" ionization can occur, but a μ^+ can only lose energy by the recoil in elastic atomic collisions. Since the Ag Br are heavier, they are less effective in stopping the μ than the CNO of the gelatine; so though the μ^+ may find itself in the Ag Br as it reaches the end of ionization, it may leave the grain before it comes to rest. Note that this effect might be sensitive to grain size.

Finally we discuss: where should one look for triplet muonium, detecting it by its precession in weak external fields? The answer: in partially depolarizing materials, preferably liquids, at high temperatures. This is because no depolarization implies no muonium (as was recognized by Telegdi, et al); whereas complete depolarization implies that triplet muonium is strongly affected by local fields. The effect of local fields, as in nuclear resonance work, is minimized in liquids and at high temperatures.

DISCUSSION

LEDERMAN: Let me comment about the emulsion problem, in view of the Minnesota results. We spent a few days with emulsions, and first tried Ag Br by itself and found that what Goebel just said is true -- i.e. no asymmetry effect or complete depolarization. We next tried Ilford gelatin since we thought that gelatin plus Ag Br gives emulsion. But we found that gelatin gives exactly the same result as emulsion, so that it seems that μ^+ prefer to stop in gelatin much more than one would expect from the stopping powers which give a 50-50 ratio. However, gelatin does contain some glycerine and it is conceivable that a mixture of gelatin and glycerine might be better than pure gelatin. So we tried three batches of emulsion supplied by Ilford, each of which had a missing secret ingredient. We found all of them to give the same result, $\alpha = -.14$.

CASSELS: I thought I would just mention that we have a list of materials in Liverpool in which triplet muonium is not observed, and in fact CCl_4 is now a record material for no muonium at all.

WILLIAMS: I'd like to ask Kaplon if he has the numbers for the confidence limits on whether the cosmic ray emulsion data could be consistent with the others?

KAPLON: I think it could be. The cosmic ray average results were $.09 \pm .02$. The machine results were .15 with essentially the same error. So these are about two standard deviations apart, which amounts to a 5% to 10% probability. I would like to point out, with respect to this gelatin cooking business just mentioned by Lederman, that the Cambridge group (Wilkinson) obtained some emulsion from Ilford that contained twice as much gelatin as ordinary emulsion. They observed an enhanced asymmetry coefficient of 0.19 for the diluted emulsion.

TELEGDI: I would just like to say that Dr. Goebel's candid discussion furnishes at best a model. The formation of such an object as muonium in a solid is subject to some discussion, because in the velocity range in which muonium could be formed - which is the Bohr velocity - the muonium could make 10^{16} collisions per second, and it can disintegrate, form, and reform. If it is in the mixed state which has a depolarization due to hyperfine structure, and you interrupt this process sufficiently frequently, you have a random walk problem and you have to add the squares of the individual precession angles. This can decrease the effect appreciably. In fact, 10^{-16} seconds is a time comparable with the time of precession of an electron in its muonium orbit, so to speak of such a stable system is to stretch one's imagination.

In experiments where polarized nuclei, formed by the capture of polarized neutrons, emitted electrons, and a longitudinal field increased the observed effect, we can by no means speak of the destruction of muonium. It is just that neighboring electrons that contribute perturbing fields are made to precess by the application of an external field. However, the Paschen-Back effect of the type we are measuring with counters would tend to reestablish asymmetry, whatever the mechanism is. If the mechanism were the formation of muonium, then the sole parameter for the field dependence for reestablishing the asymmetry would clearly be a function of the electron magnetic moment times the magnetic field divided by the splitting. So if you measure the field dependence you can see whether it is muonium or not, because if it were something else the triplet-singlet difference of muonium would not enter.

One other point. Triplet muonium, as Dr. Goebel has pointed out, would precess in weak fields. The singlet part would destroy itself by hyperfine structure. But you have two kinds of experiments: those in which you make things precess in an external strong field, and those which carefully avoid strong fields such as emulsion and bubble chamber experiments. Whereas in an experiment involving a strong external field the entire amount winding up in muonium would be subtracted from the asymmetry, in the absence of that field only one-half disappears. So again one would have a quantitative way of checking these things.

As to the Lattes, Fowler, and Company Minnesota experiment, there is a question to be raised before taking the mean, namely are all these samples from a "normal population"? Are they distributed in a random fashion, or is this just one sole result that stands by itself? Now that we know that the famous Minnesota result is not due to the composition of the emulsion (I would like to point out that the emulsion we measured was from the same batch and also undeveloped) it would be interesting to examine this question. Perhaps there is someone here who is more competent to judge how much reliance we should place in the Minnesota result.

GOEBEL: I would like to reply to Telegdi's points. First of all, there is no question about the singlet muonium depolarizing while slowing down. In fact the slowing down takes less than 10^{-10} seconds. Regarding the question of the formation of muonium, I think there is no doubt that it is formed. First there is the negative argument I gave--that I couldn't find anything else to account for depolarization. Secondly, positronium is formed in many solids, and after all muonium is bound twice as tightly as positronium. It is hard to see why it should be less easily formed.

I would like to make one more comment on the experiment in boron carbide. Of course only the components of spin perpendicular to the magnetic field precess, and therefore the boron carbide effect could be from triplet muonium with its spin along the magnetic field (the other components having been erased) that is being converted by local fields into the singlet state.

WERLE: Theoretical considerations on $K_{\mu 3}$ decay.

I shall discuss briefly the implications of the two-component neutrino theory on $K_{\mu 3}$ and $K_{e 3}$ decay. The reactions are

$$K \longrightarrow \pi + \mu(e) + \nu \quad \text{(polarized)}.$$

Since we now know that the neutrino emitted in this reaction is completely polarized in the longitudinal direction, this implies that the muon or electron will also be at least partially polarized, in spite of the presence of a third body, the pion. Of course the polarization won't be complete as in $\pi - \mu$ decay because of the presence of that third body.

Since we don't know very much about the nature of the coupling which is responsible for the decay, the only possible approach is a semi-phenomenological one. Namely, we can construct a quite general form of the transition matrix by assuming that the muon and neutrino (or the electron and the neutrino) are created simultaneously, and that neither of these particles interact afterwards with any other virtual or real particle. This general form contains four possible coupling types, and it can be shown that after imposing suitable invariance restrictions the expression for the longitudinal polarization becomes

$$\Pi(p) = \frac{\sum_{i=1}^{6} a_i \left[L_i(p) - L_i(-p) \right]}{\sum_{i=1}^{6} a_i \left[L_i(p) + L_i(-p) \right]},$$

where

$$a_1 = C_T^2, \quad a_2 = C_S^2, \quad a_3 = C_V^2, \quad a_4 = C_V'^2, \quad a_5 = 2C_S C_T, \quad a_6 = 2 C_V C_V'.$$

All the C's are real. The functions $L_i(p)$ depend on the momentum p of the muon or electron and on the masses of these particles. It turns out that $\Pi(p)$ depends in a sensitive way on the type of coupling. In particular, the polarization curves of the muon drawn for the four pure cases S, V, V', T show rather striking differences which partly disappear in the case of electrons. This is due to the smallness of the electron mass and to the relativistic energies of the electron. According to the present theory, measurement of the polarization of the muon in K decay would provide valuable information on the nature of the couplings involved.

APPENDIX

KOTANI: Muon decay.

In muon decay, there are three measurable quantities: namely, the unit vector along the polarization of a mu - meson, $\vec{\xi}$, the unit vector in the polarization direction of an electron, $\vec{\sigma}$, and the electron momentum, $\vec{x}$. The general expression for the distribution function in electron momentum, its direction, polarizations of electron and mu meson is given by

$$W(\vec{\xi}, \vec{\sigma}, x) = \lambda\, dx\, d\Omega_e \frac{1}{8\pi}$$

$$\times\left[A + B\frac{\vec{x}\cdot\vec{\xi}}{x} + C\frac{\vec{x}\cdot\vec{\sigma}}{x} + D\,\vec{\xi}\cdot\vec{\sigma} + E\frac{(\vec{\xi}\cdot\vec{x})(\vec{\sigma}\cdot\vec{x})}{x^2} + F\frac{\vec{\sigma}\cdot(\vec{\xi}\times\vec{x})}{x}\right],$$

where the 6 coefficients, A to F, are functions of coupling constants and the magnitude of the electron momentum, and $1/\lambda$ is the muon lifetime.

For a muon at rest, with spin completely polarized, the general angular distribution function of electrons is given by the three parameter formula

$$\frac{\lambda}{4\pi}\left[A + B\frac{\vec{\xi}\cdot\vec{x}}{x}\right] dx\, d\Omega_e$$

$$= \frac{\lambda}{4\pi} 2x^2\left\{\left[6(1-x) + \frac{4}{3}\rho(4x-3)\right] + \xi\cos\theta(1-2\alpha x)\right\} dx\, d\Omega_e ,$$

neglecting the mass of electron compared with its momentum. Here θ is the angle between the spin of the muon and the momentum of the electron.

In order to see the characters of these coefficients (C to F) and three parameters (ρ, ξ, and α), let us consider only the process

$$\mu^{\pm} \longrightarrow e^{\pm} + \nu + \bar{\nu}$$

in which the two neutrinos are distinguishable. Also, for simplicity, I should like to restrict my report to the special two-component theory of the neutrino ($\psi_\nu = -\gamma_5 \psi_\nu$) and to show only the available range for the observable quantities. (The definitions of the coefficients are written in UCRL Report No. 3704).

Interaction Hamiltonian	$(e,\mu)(\bar{\nu},\nu)$	$\underbrace{(\mu,\bar{\nu})(e,\nu) \quad \text{or} \quad (\bar{\nu}\,\mu)(e,\nu)}$	
Type of Coupling	(V, A)	(S), (P), (S,P)	(V), (A), (V,A)
ρ	0.75	0.75	0.75
α	1	1	1
ξ	$1 \geq \xi \geq -1$	b	-b
$P_L = \frac{[C+(D+E)\cos\theta]\,dx\,d\Omega_e}{[A+B\cos\theta]\,dx\,d\Omega_e}$	$1 \geq P_L \geq -1$	-b	b
$P_T = \frac{F\,dx}{A\,dx}\,\lvert \vec{\xi} \times \vec{x} \rvert$	$1 \geq P_T \geq -1$	0	0

Here "b" means (+1) or (-1) corresponding to the positive or negative energy state of the mu - meson. "P_L" is defined that the positive value of this P_L means the polarization of electron is in a direction parallel to its momentum. "P_T" is derived from the last term F of the general expression which violates both space and time reversal invariances. This P_T could be detected by the method which was proposed by Drs. Tolhoek and de Groot. In this case, the polarization of the electron in a direction perpendicular to its momentum could be observed.

If we assume the conservation of light particles, experimental results for ρ, ξ, and α, which were reported just before, are nearly equal to the values which were given in the last column of this table. But there are a little differences. Therefore, we may have to consider the combination of these two groups, for example, S- and V- coupling types, if we assume the interaction Hamiltonian density in the charge exchange order. I hope the future experiments will give definite values for the five observable quantities which are given in the last column of the above table. If it is the case and the conservation of lepton number is assumed, the positron in μ^+ meson decay is completely polarized in the direction antiparallel to its momentum and the electron is also completely polarized in the direction parallel to its momentum. This polarization depends neither on the energy nor on the angle of emitted particles in this special case, in which the electron mass is neglected.

AMALDI: Angular Correlation in π-μ-e decays.

When, last spring, the preprint of Lee and Yang paper was received in Rome, Mr. Gatto pointed out to the emulsion group the problem which was discussed in it, and immediately Castagnoli, Franzinetti, Manfredini started to measure the angular distribution of electron emitted in π-μ-e decays.

The events used were those collected during a previous experiment in a stack of Ilford G-5 600 μ m thick emulsion exposed at high altitude to cosmic rays (about 30 Km) during the Sardinian Expedition 1953.

At the Avogadro Conference, held in Turin at the beginning of September 1956, preliminary results were presented, based on 410 events. The value of a, as defined in the expression of the angular distribution $f(\omega) = 1 + a \cos\omega$ suggested by Lee and Yang, was determined by the least square method and found to be

$$a = -0.13 \pm 0.10.$$

The measurements were continued and on a total of 1028 events, Castagnoli, Franzinetti, and Manfredini (N. Cim., 5, 684, 1957) found

$$a = -0.222 \pm 0.067$$

as the best fitting parameter determined using the least square method; and

$$a = -0.218 \pm 0.07$$

from the forward-backward asymmetry.

Care was taken to evaluate experimental biases. It could be seen, for instance, that very steep electrons were sometimes missed. From elementary geometrical considerations, the validity of which was checked experimentally, the relative loss of events has been calculated as a function of cos ω

Apart from the 1028 events and those which have been neglected because they did not satisfy our selection criterion (see N. Cim., 5, 684, 1957), the following cases were found:

5 associated with a very slow electron; in these cases the association with the primary μ was doubtful.
14 with a very large gap in the initial part of the electron track.
5 probably to be explained as due to diffusion (see below).
9 without any visible electron.
33

Using the calculated "loss function" P(ω), the experimental distribution was "corrected". The correction takes in to account those which do not satisfy the selection criterion but not the 33 listed above.

The energy of 221 emitted electrons has been determined on the basis of multiple scattering measurements.

Preliminary results, based on the available statistics give

		F	B
$N(B)/N(F) = 1.6 \pm 0.8$	$E < 25$ MeV	25	42
$N(B)/N(F) = 1.38 \pm 0.4$	$E > 25$ MeV	61	93

Further measurements are in progress.

In connection with the problem of the polarization of μ stopped in the emulsion, we have investigated the possibility that once reduced to thermal energy, the μ may diffuse without ionizing through an appreciable distance before decaying.

Out of all the events mentioned above, only four cases have been found in which the position of the first grain of the electron and its direction of motion are such as to suggest the possibility of the interpretation given above - but on the other hand it must be pointed out that the disalignment is within the limits of the expected fluctuations in the position of the developed grains with respect to the original path of the ionizing particles.

HAYAKAWA: Polarization of cosmic ray μ -mesons.

In connection with an experiment (G. Clark, R. D'Arcy and J. Hersil, private communication) of observing the polarization of cosmic ray μ mesons at sea level, the expected degree of polarization is calculated, by taking account of the energy spectrum of π mesons and the depolarization caused by the scattering in the atmosphere and the roof.

According to the two-component neutrino theory, which seems to be well established through various experiments with β -rays and artificial mesons, the μ -meson in the rest system of the parent π -meson is completely polarized along the direction of its momentum. Since the μ -mesons we are observing come from the π - mesons of high energies, around 3 Mev, the polarization is no longer complete. In reference to the transformation property of the polarization (H. A. Tolhoek, Rev. Mod. Phys. 28, 277 (1956)), the degree of polarization along the direction of the μ -meson is obtained as

$$[p^* + (\vec{p}^{*} \cdot \vec{v}\,')/v^*] \,/\, p(1 - \vec{v}\,'^2)^{\frac{1}{2}} ,$$

where p* and v* are the momentum and the velocity of the μ -mesons, respectively, in the rest system of the parent π -meson and $\vec{v}\,'$ is the velocity of the π -meson in the laboratory system.

Assuming a power law for the energy spectrum of π -mesons,

$$\pi(E)\, dE = \pi_0 E^{-\alpha-1}\, dE,$$

the degree of the polarization is averaged over the energy spectrum. The result is simply given by

$$(1 + \alpha)\ v v^*/3$$

to first order in vv*, where v is the velocity of μ -mesons in the lab system. Since this is a slowly varying function, averaging over the energy spectrum of μ -mesons and over the production heights is unimportant.

The depolarization due to Coulomb scattering is evaluated to be about 14% from the production to the entry to the apparatus. In the stopping copper layer, the depolarization due to the scattering is negligibly small, because the electric field alone is ineffective in the depolarization. The effect of the muonium formation is not discussed.

Altogether we expect about 20% polarization minus some unknown depolarization mainly due to the muonium formation.