THE EXPERIMENTAL STATUS OF THE WEAK INTERACTIONS OF NON-STRANGE PARTICLES (*)

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I. INTRODUCTION

Our present theoretical description of the leptonic interaction of the ordinary particles is summarized by the so-called Puppi triangle supplemented by the rules of lepton conservation and the assignments of neutrino helicity ($\nu = \nu_L$, $\bar{\nu} = \nu_R$), and the hypothesis that the μ and e neutrinos are the same objects.

A charged and a neutral particle appear always together at the vertices, and never two charged particles. Hence processes like

$$N + \mu^- \rightarrow N + e^- \qquad (1)$$

and

$$e^- + \mu^- \rightarrow e^- + e^- \qquad (2)$$

are not supposed to occur.

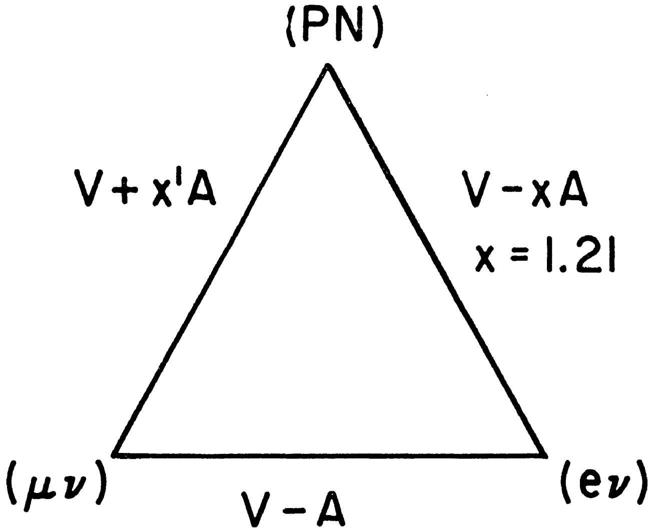

Fig. 1 The Puppi triangle.

There are no experimental facts in contradiction with this description, but it is the experimentalist's task to check all the observable consequences of this very appealing unified description with ever increasing accuracy.

Perhaps the more significant lacking piece of experimental evidence was the consequence of lepton conservation. That is, in the decays

$$\pi^{+(-)} \rightarrow \mu^{+(-)} + \nu^{(-)} \qquad (3)$$

one should observe

$$\mu^{+(-)} = \mu_{L(R)} \qquad (4$$

(one has in β decay $e^{+(-)} = e_{R(L)}$), but to slow down process (3) and in particular its electron analogue, the μ has to be produced with the "unwanted helicity".

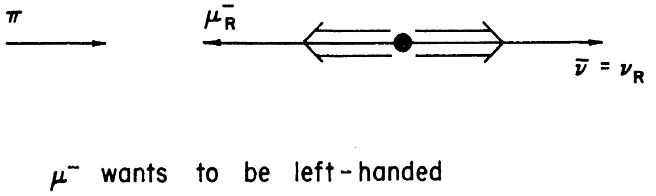

Fig. 2 μ and ν helicity.

An elegant experiment by Alikhanov and coworkers [1] presented at this Conference seems to check Eq. (4). This experiment consisted in studying the Møller scattering of polarized cosmic ray μ's of either sign from polarized electrons. The observed polarizations are.

(*) Editor's Note : This is a revised version of Dr. Telegdi's talk sent to us after the conference.

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$$P_+ = -(0.15 \pm 0.21)$$

$$P_- = +(0.65 \pm 0.22)$$

(with + corresponding to right, and − to left). Averaging over both signs of charge $|P| = 0.38 \pm 0.15$.

This magnitude of P is not in disagreement with theoretical estimates. The experiment will no doubt be continued to obtain better statistics. A similar experiment, in progress at CERN with μ's from the Proton Synchrotron will probably be performed before the next meeting.

The Russian helicity experiment is of particular interest, because an alternative way to measure μ^- helicity met with serious difficulties. (Via the polarization of the B recoil nucleus in the process:

$$\mu^- + C^{12} \to B^{12} + \nu \qquad (5)$$

probably due to processes tending to depolarize B^{12} during its 20 ms lifetime.) The positive results of the Carnegie group, discussed in Alikhanov's Kiev report, have in the meantime been retracted [2].

The non-existence of processes of the type (1) and (2) has been reinvestigated during the last year with greatly increased accuracy. One of these investigations was described in a contributed paper from Berkeley [3]. A very similar experiment was performed by a Rome group [4] at CERN. The results of both experiments will be summarized in a following section of this report.

A very fundamental problem is the identity of the neutrinos appearing at the two bottom vertices of the Puppi triangle. This problem, to my knowledge first raised by Nishijima, has recently become the object of intense speculation. It can clearly be settled only by *observing* whether the neutrino associated with one vertex can induce the direct production of the charged lepton associated with the other vertex. Such experiments, although very difficult, are in active preparation and were discussed at this Conference by Markov and by Bernardini [5]. They need no further discussion here.

We shall discuss recent experimental evidence concerning the three sides of the Puppi triangle in inverse order to the amount of knowledge which is already available concerning the pertinent processes. This should enable the rapporteur to cover in the limited time available at least those sections which contain most new information.

II. THE $(NP)(\mu\nu)$-LEG : μ^- ABSORPTION

(a) Absorption rates in complex nuclei

This is a field where our ignorance is such that we have just barely obtained experimental evidence that parity is not conserved. Not only do we ignore the magnitude of x', defined as

$$x' = G_A^\mu / G_V^\mu \equiv A/V \qquad (6)$$

(where A, V are effective coupling constants). We have little proof that the Fermi (V) coupling is present at all! The main difficulty which one encounters over and over again is caused by the fact that between us and the truth lies the barrier of nuclear physics. The fundamental process

$$p + \mu^- \to n + \nu \qquad (7)$$

has not been studied so far. The situation in μ capture is similar to the one we would face in β decay if the free neutron decay were not accessible to study and if the super-allowed transitions with *a priori* known matrix elements did not exist.

Experimental observations concerning Eq. (7) could clearly be interpreted directly in terms of the fundamental coupling constants. However, most experts were until recently of the opinion that " molecular " problems—the formation of μ-mesic molecules or mulecules in liquid H_2—would not present a satisfactory interpretation. Recent theoretical work at Berkeley, in particular by S. Weinberg [6], has shed much light on this matter. A capture experiment in liquid H_2 appears now both feasible and interpretable, and we shall discuss this matter below.

We summarize a few useful notions. The muon can exist in the 1s Bohr orbit about a proton in two states $F = 0, 1$. It would be natural to define the coupling constant in terms of the absorption rates Λ_0, Λ_1 in these states—the only two operationally defined quantities for unpolarized μ's. However, this is not the traditional way, and one has (neglecting consistently the effective pseudoscalar interaction specified by a constant P).

$$\text{(triplet)} \qquad \Lambda_1 \sim (V+A)^2 \sim (1+x')^2 \qquad (8a)$$

$$\text{(singlet)} \qquad \Lambda_0 \sim (V-3A)^2 \sim (1-3x')^2 \qquad (8b)$$

$$\bar{\Lambda} = \frac{3}{4}\Lambda_1 + \frac{1}{4}\Lambda_0 \sim (V^2 + 3A^2) \sim (1+3x')^2 \qquad (8c)$$

Note that $\Lambda_1 = \Lambda_0$ for a spin-independent interaction ($A = 0$), and that $\Lambda_1 = 0$ for $x' = 0$ (the $V-A$ interaction). The spin dependence of the interaction can be studied in principle by measuring

$$\delta_p = \frac{\Lambda_0 - \Lambda_1}{\bar{\Lambda}} = \frac{8(x'^2 - x')}{1 + 3x'^2} \equiv 4\frac{b}{a} \tag{9}$$

$$x = 1.25 \text{ in } \beta\text{-decay}$$

the x' dependence of δ_p being illustrated by Table I

Table I

x'	∞	-1.25	0	$+1.25$
b/a	$-^2/_3$	$+1$ $\Lambda_0 > \Lambda_1$	0	-0.11 $\Lambda_1 > \Lambda_0$

With polarized μ's one can study the angular distribution of the emitted neutron. Clearly, for $x' = 0$, all the μ's are absorbed from a $F = 0$ state, and their angular distribution will be *spherically symmetric*. The simplest $V-A$ interaction predicts isotropic neutron distributions. For bound protons, nuclear physics can only decrease the observed asymmetry.

The two hyperfine states (here $F = 1$ and 0) and their analogue in complex nuclei, may convert into each other at a rate R. Suitable atomic processes exist both in the case of liquid H_2 and of solids containing complex nuclei.

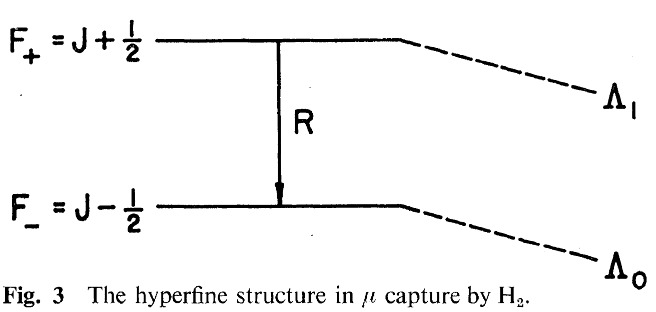

Fig. 3 The hyperfine structure in μ capture by H_2.

The capture rates in complex nuclei are well described by the Primakoff [7] formula

$$\frac{\Lambda(Z, A)}{Z_{\text{eff}}^4} = \gamma \cdot \bar{\Lambda}(1, 1) \cdot P(n) \tag{10}$$

where γ is the ν phase space and recoil correction. $\bar{\Lambda}$ (1,1) is the proton absorption rate; $P(n)$ is the Pauli inhibition $P(n) = 1 - \frac{n}{2}d$; $n = \frac{A-Z}{A}$ is the fractional n excess. Primakoff estimates γ with ±20% uncertainty; $d = 3.15$ from experiment [8] which also gives $\Lambda(Z, A)$ directly. $\bar{\Lambda}(1,1)$ can be calculated from assumed coupling constants.

$\gamma\bar{\Lambda}_{\text{exp}} = 188 \text{ sec}^{-1}$

$\gamma\bar{\Lambda}_{\text{the}} = (161 \pm 30) \text{ sec}^{-1}$ (canonical set of coupling constants)

$\gamma\bar{\Lambda}_{\text{the}} = (112 \pm 20) \text{ sec}^{-1}$ (putting $V = 0$)

This last case can just barely be excluded. The best agreement is given by the canonical set [7]. An interesting effect of $P(n)$ is that two isotopes could exhibit appreciably different capture rates.

For $\Lambda(\text{Cl}^{37})/\Lambda(\text{Cl}^{35})$ Eq. (10) predicts a value of 0.83, e.g. 17% effect. A recent Carnegie Tech. experiment described in a paper [9] gave the result

$$\Lambda(\text{Cl}^{37})/\Lambda(\text{Cl}^{35})\Big|_{\text{exp}} = 0.694 \pm 0.034$$

in reasonable agreement with Primakoff's formula. It would be of interest to see whether shell model calculations (mentioned elsewhere in this report in another context), could match experiment better.

(b) Spin dependence and hyperfine effect

As first pointed out by Bernstein, Lee, Yang and Primakoff (BLYP) [10] a measurement of the difference in the capture rates of the two incoherent h.f. levels of a mesic atom with non-zero spin nucleus—the analogue of δ_p defined in Eq. (9) for the free proton—could yield valuable information on spin dependence. Eq. (9) is readily generalized to

$$\delta = \frac{\Delta\Lambda}{\bar{\Lambda}} = \frac{1}{Z}\delta_p \cdot \frac{\langle \mathbf{J} \cdot \mathbf{S}_p \rangle}{J(J+1)} \cdot \frac{2J+1}{2} \left\{ \frac{P(n)_{\text{outer}}}{P(n)_{\text{core}}} \right\} \tag{12}$$

(As $Z \to 1$, the two last terms go to unity.) If one cannot distinguish operationally the two capturing states, then the plot of the *electron* decay rate $\Lambda_t = \Lambda_{\text{decay}} + \Lambda_{\text{capture}}$ has a curvature $K \sim \delta^2$ and one does not learn which state decays faster.

It has been pointed out[11] that e.g. in Al there exists a rapid conversion mechanism (by magnetic Auger effect) from the upper ($F=3$) to the lower ($F=2$) h.f. level. In[11] the conversion rate R ($\leq 0.5\Lambda_t$ in Al) was estimated and it was shown that the curvature K, defined as

$$K=-\frac{1}{\sqrt{8}}\cdot\left[\frac{J+1}{2J+1}\cdot(\delta')r-\frac{J+1}{2J+1}\,\frac{J}{J+1}(\delta')^2\right] \qquad (13)$$

where

$$\delta'=\Delta\Lambda/\Lambda_t,\; r=R/\Lambda_t$$

becomes negative when R is sufficiently large ($\gtrsim\Delta\Lambda$), and $\delta'>0$ (when the F (" singlet ") state decays faster). Preliminary results of the Chicago group were presented at Kiev, and the reliable results are now available for both Al and P. We shall discuss them and show that they indicate an interaction of the type $V-x'A$ in μ^- capture[12]. By fitting the data to an expansion about a mean exponential plus background (like)

$$e^{-\alpha t}\left[a_0+a_1(\alpha t)+a_2(\alpha t)^2+a_3(\alpha t)^3\right]+B$$

one obtains the Figs. 4 and 5 for Al and P respectively.

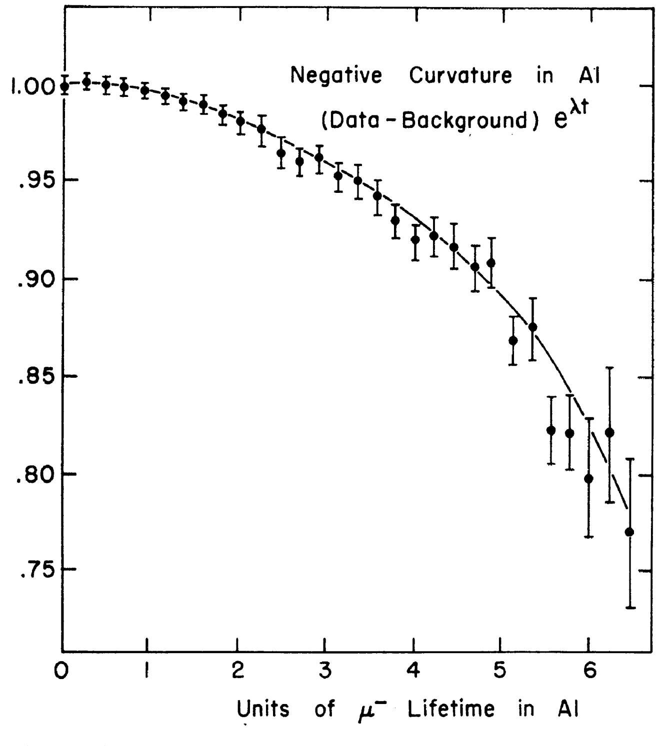

Fig. 4 Aluminium hyperfine data.

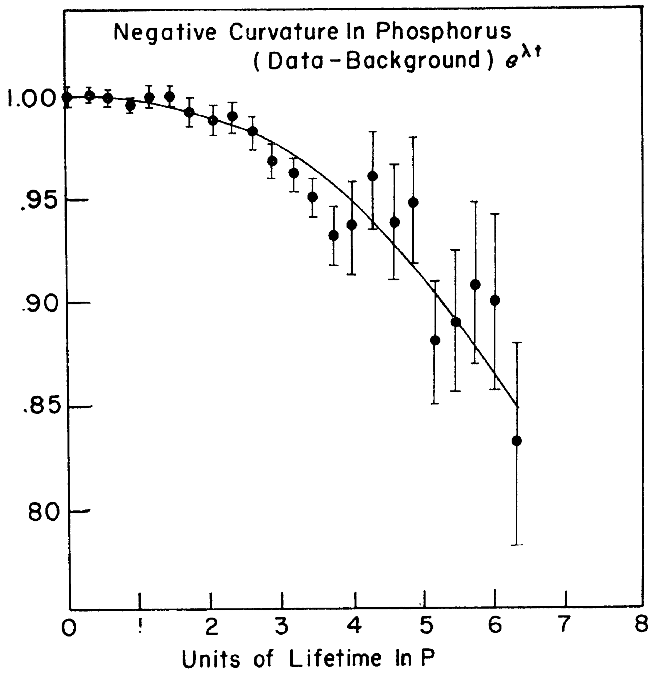

Fig. 5 Phosphorus hyperfine data.

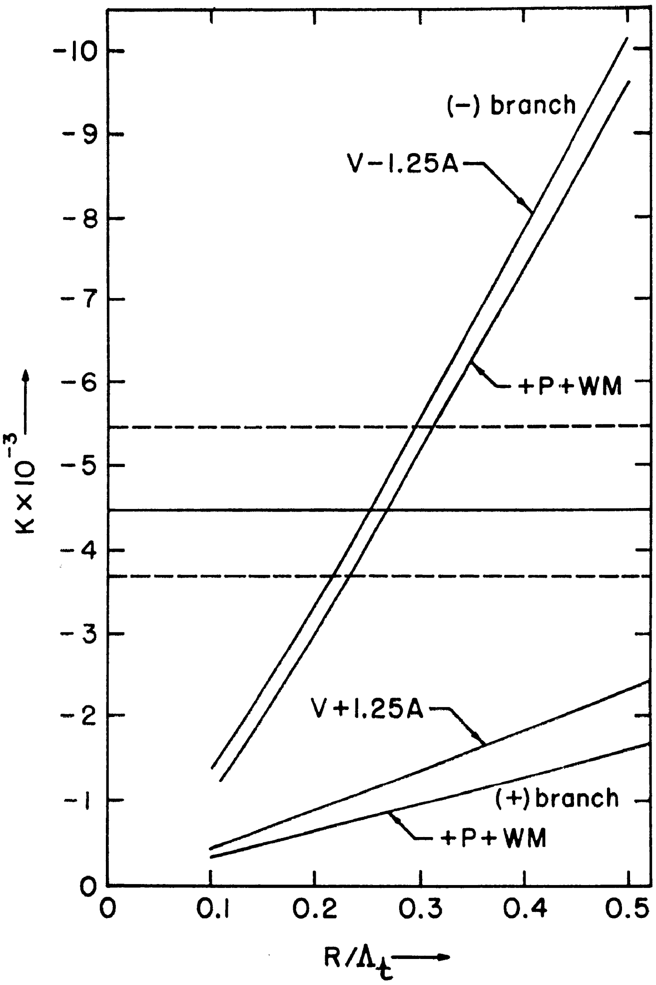

Fig. 6 Curvature versus conversion rate for BLYP calculations of $V\pm1.25A$.

The negative curvature found experimentally is quite pronounced. In fact,

$$\text{Al} \quad K = -(4.4 \pm 1) \times 10^{-3}$$

$$\text{P} \quad K = -(6.9 \pm 2) \times 10^{-3}$$

Decision between $(V + x'A)$ and $(V - x'A)$ could be done by appeal to Fig. 6 computed using $x' = 1.25$; $\delta = \Delta\Lambda/\Lambda_t$ was taken from BLYP. Überall[13] has computed δ' on the shell model and finds larger values than BLYP.

Figs. 7*a* and 7*b* show pairs of values of $r \equiv R/\Lambda_t$ and $\delta \equiv \Delta\Lambda/\Lambda_t$ compatible with experiment. The predictions by BLYP (Al, $\delta = 0.10$; P, $\delta = 0.20$) and Überall (Al, $\delta = 0.17$; P, $\delta = 0.32$) are indicated using $x' = -1.46$. Either model gives for $x' = +1.46$ very small δ's compatible with experiment only for an unreasonably high conversion rate.

Thus one can see independently of any model and of the canonical magnitude that $x' < 0$.

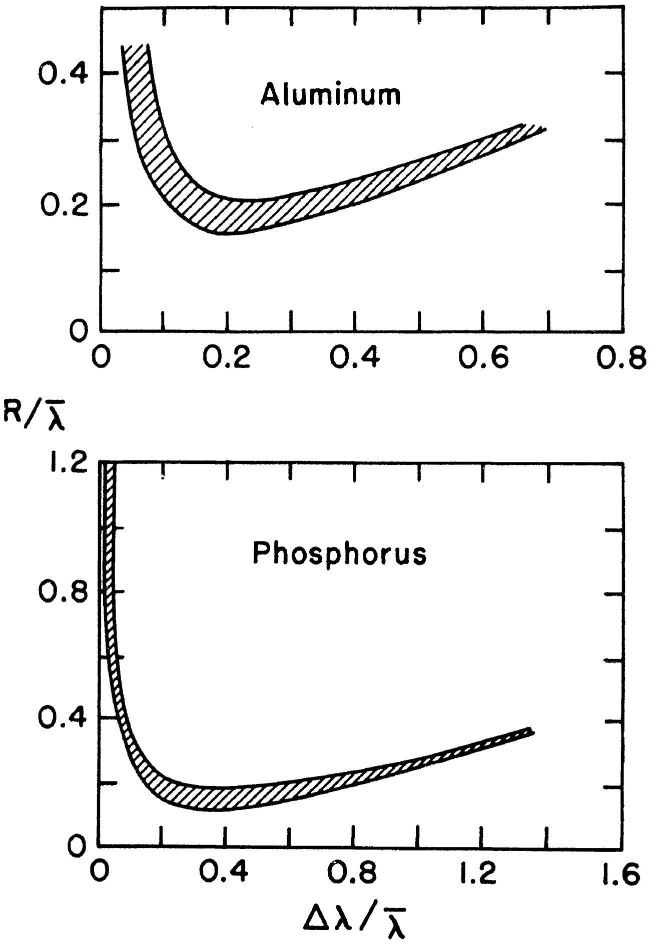

Fig. 7 Values of R and δ compatible with observed curvature. *(a)* for Al; *(b)* for P.

(c) Asymmetry of the neutron distribution

The neutrons produced in the capture of polarized μ's by complex nuclei may have an asymmetry distribution of the form $1 + \alpha \mathbf{P}_\mu . \mathbf{k}_n$, where $\mathbf{P}_\mu$ specifies the μ polarization ($|\mathbf{P}_\mu| < 1$) and $\mathbf{k}_n$ is a unit vector in the direction of neutron emission. The coefficient α depends on the type of coupling as well as on nuclear physics.

The interest of determining α is twofold.

(1) $\alpha \neq 0$ is a direct proof of parity non-conservation;

(2) For $x' \approx -1$, α vanishes. The induced pseudoscalar coupling, P, a higher order effect in some aspects of μ physics, dominates α, and in fact (for $x' \approx -1$) the sign of α depends on the sign of the ratio A/P. This latter sign can be predicted theoretically[14, 15].

The experimental situation looked confused during the last year. W. F. Baker and C. Rubbia found for Mg and S positive values of α which were within one standard deviation equal to zero[16]. A Liverpool group[17] found (in S)

$$\alpha \mathbf{P}_\mu = -(4.5 \pm 1.5) \times 10^{-2}.$$

The techniques used in these two experiments were very different. Baker and Rubbia used sandwich counters to discriminate against the (probably isotropic) x-rays, and delayed gates to see the precession. The Liverpool group used a Brooks-type counter to achieve the same discrimination and displayed the precession as a function of time. Fig. 8 shows this result.

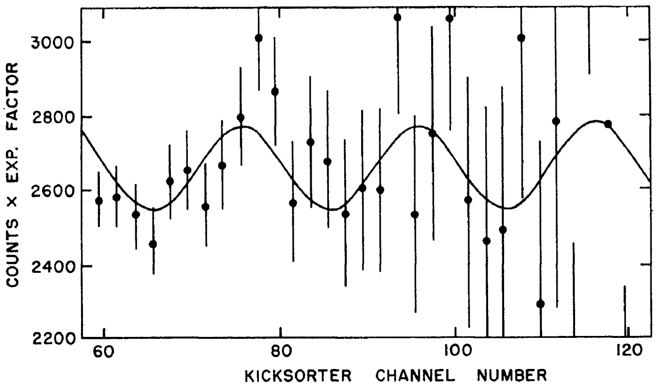

Fig. 8 Neutron asymmetry data of Astbury et al.

Recent work at Chicago[18] has revealed an asymmetry in both S and Mg, and thus confirmed the work of the Liverpool group. The Chicago experiments were done with effectively the same technique as used at Liverpool. The " precession " of the γ-rays and of neutrons of energy greater than 5 MeV was however recorded simultaneously, and the background conditions were cleaner than in Liverpool.

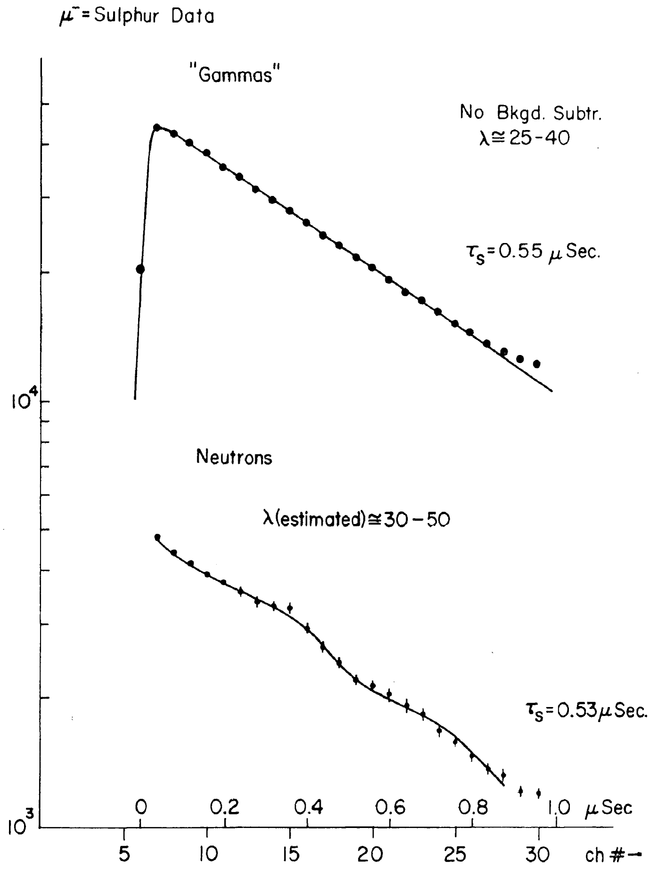

Fig. 9 Comparison of gamma and neutron time distributions for μ^- in sulfur.

Fig. 9 shows the observed time dependences of the " γ " and " neutron " counts from S. The difference between the two shows that the *neutron* asymmetry is unlikely to be due to experimental causes. Figs. 10 and 11 show the precession curves for μ decay electrons and neutrons for S and Mg. The comparison of these two eliminates the magnitude of $\mathbf{P}_\mu$; the neutron asymmetry is seen to be almost the same as the electron asymmetry (where $\alpha \cong -1/3$), both in magnitude and in sign. The large magnitude *and* the negative sign of α (assuming the helicity of μ to be positive) bears out the theoretical prediction that $P/A > 0$.

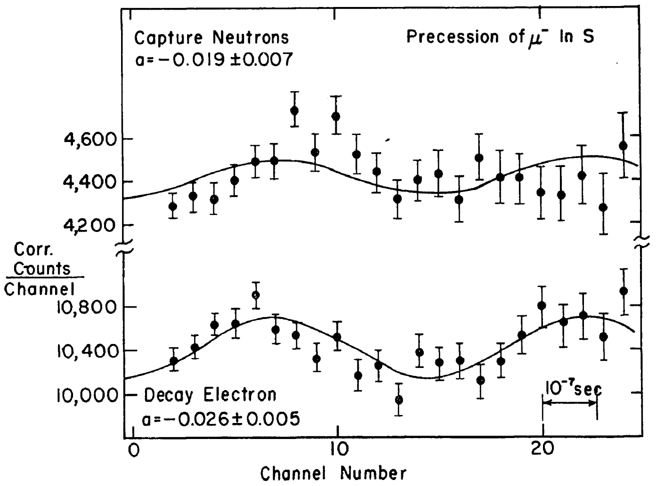

Fig. 10 Neutron and electron asymmetries for μ^- in sulfur.

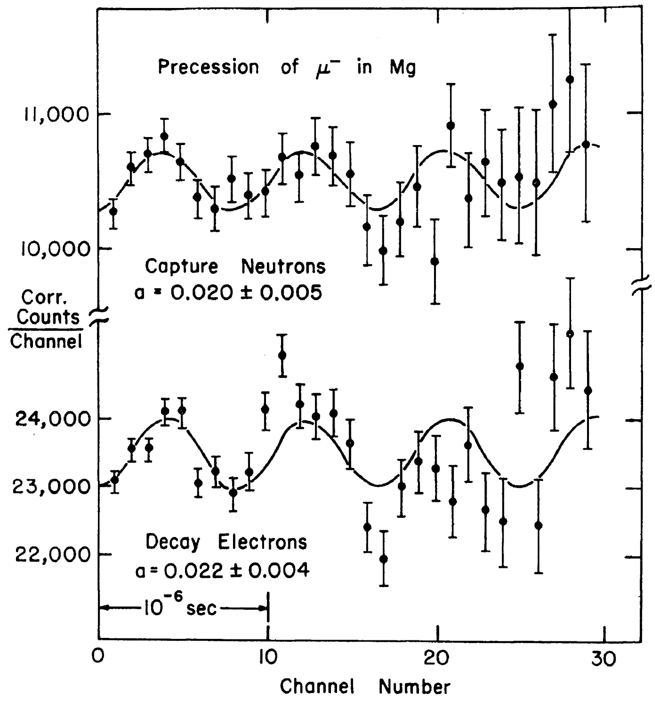

Fig. 11 Neutron and electron asymmetries for μ^- in magnesium.

(d) μ-Capture in H_2

In view of the difficulties which the correct prediction of nuclear matrix elements etc. presents, it is our opinion that μ-absorption experiments with complex nuclei, even if greatly improved, will reveal at best only the qualitative features of the effective interaction. The investigation of the fundamental process

$$\mu^- + p \rightarrow n + \nu$$

had appeared most desirable for a number of years. For the actual absorption experiment, liquid hydrogen usually was contemplated, because of its density. After the discovery of muon-induced fusion, people realized the complicated atomic and molecular situations in which muons find themselves in liquid—even if pure—hydrogen, and the possibility of correctly interpreting the observed absorption rates in terms of the long-sought coupling constants appeared remote.

The questions which one has to answer, granted the availability of isotopically and chemically pure H_2, are at least the following ones :

1) what fraction of their lifetime do the μ^-'s spend as $(p\mu^-)$ atoms, and what fraction as $(p\mu p)$ " molecules " ?

2) what are the populations, of specified relative μ-p spin orientations S, $(\mathbf{S} = \mathbf{S}_\mu + \mathbf{S}_p = 0{,}1)$ in the relevant μ-atoms and molecules, at the instant of capture?

3) what are the exact probabilities, $|\psi(0)|^2$, for finding the muon at the proton(s) in the systems of interest?

From a practical point of view, the following questions are of interest if hydrogen of the required purity is not available :

4) what is the perturbing role of the deuterium contamination of hydrogen of normal isotopic composition?

5) what is the perturbing role of impurities other than d?

It would be improper to discuss the hydrogen problem, so far an entirely theoretical one, in this report were it not for the fact that one now *knows* reasonably accurate, encouraging answers to most of the questions listed above. This is the merit of many workers in " molecular physics ", and particularly of S. Weinberg of Berkeley, who has recently evaluated the whole problem critically [6]. We summarize now Weinberg's conclusions briefly.

The right-hand side of Fig. 12 illustrates the fate of a μ^- stopped in pure liquid H_2; the left-hand side of that figure indicates an additional sequence of reactions which occur when the hydrogen is not isotopically pure. At normal isotopic d-concentration, probably $\sim 30\%$ of the muons emerge in that sequence.

According to Fig. 12, the $F = 1$ $(p\mu)$-atoms are rapidly converted (by collisional exchange, the Gershtein-Zeldovitch mechanism) into $F = 0$ $(p\mu)$-atoms. These become rapidly (within $\sim 1/10$ muon lifetimes) $(p\mu p)$-molecules in the ortho, $L = 1$ state (proton spins *parallel*). According to Weinberg's estimate, the conversion to the para, $L = 0$ state is negligibly slow.

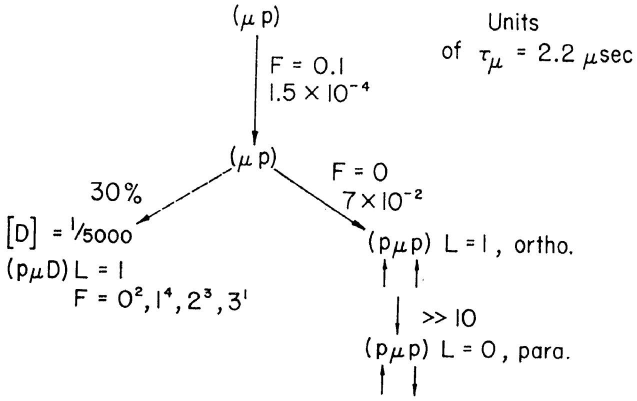

Fig. 12 Evolution of a μ^- captured in liquid H_2.

The total spin, S, of the muon and the two protons in the ortho molecule could be either 1/2 or 3/2. Because of hyperfine interactions with L, S is however not a good quantum number; the five hyperfine states of the molecule are specified by the total angular momentum $F = 1/2(2)$, $3/2(2)$, $5/2(1)$. This important point was brought out by Weinberg.

The absorption rate in the ortho molecule is given by

$$\Lambda_{p\mu p}^{\text{ortho}} = \xi\Lambda(S = {}^1/_2) + (1-\xi)\Lambda(S = {}^3/_2),$$

when the parameter ξ satisfies

$${}^1/_2 \leqslant \xi \leqslant 1,$$

and is *perfectly calculable* from the known molecular wavefunctions. If Λ_0 is the singlet atomic absorption rate ($\Lambda_1 \ll \Lambda_0$ for any $(V-A)$ type coupling !); one has to an excellent approximation

$$\Lambda_{p\mu p}^{\text{ortho}} \simeq 2\xi\tfrac{3}{4}\Lambda_0\gamma$$

or

$$\Lambda_{p\mu p}^{\text{ortho}}/\Lambda_0 \simeq 2\xi\tfrac{3}{4}\gamma,$$

where γ is the ratio of muon density at *one* of the protons of the ortho molecule to the corresponding density in the singlet atom. Numerically, $2\gamma = 1.165$ with fair confidence. Thus the result of a muon absorption experiment in isotopically pure hydrogen is the singlet absorption rate Λ_0, expressend in terms of the *calculable* molecular parameters ξ and γ. The main uncertainty comes from our uncertainty in the fraction of time spent by the muon in an $F = 0$ $(p\mu)$-atom.

In the presence of deuterium, one has a convenient monitor of the times pent by the muon in any step of the left branch of Fig. 12 in the number of observed " fusions " or " rejuvenated muons ". At low deuterium concentrations, secondary encounters may be neglected, and one can measure the absorption rate as a function of deuterium concentration and extrapolate linearly to zero [18]. By observing the fusions, one can readily check the assumed linearity of the concentration dependence.

To suppress molecular formation, one would have to go to a gas of, say, 1/50 the density of the liquid. In such a medium, the $F = 0 \rightarrow F = 1$ conversion would still be so rapid that one would effectively be observing only Λ_0. Thus the gas experiment, while technically difficult, would not appear to be more rewarding—as we understand the situation after Weinberg's work—than that done with liquid hydrogen depleted of its normal deuterium contamination.

The problem of chemical, rather than isotopic impurities is an altogether different one. R. H. Hildebrand and M. Schiff have experimentally explored this problem [19] by direct observation in a purposely contaminated hydrogen bubble chamber. They find that He contamination, such as, e.g., found in normal " pure " hydrogen, is not necessarily very dangerous. On the other hand their studies with Ne reveal that impurities such as Ne (or, say N_2) in concentration of a few parts per million must absolutely be avoided.

It must be remarked that we ultimately want to know the magnitude of three effective coupling constants : A, V and P. The hydrogen experiment, as discussed above, yields us only one linear combination, that appearing in Λ_0. Unfortunately, this linear combination is (as long as $x' \approx -1$) rather insensitive to the small effects (weak magnetism, P) in which one is most interested. Λ_1 is far more sensitive; in fact $\Lambda_0/\Lambda_1 = \infty$ for an exact $V-A$ coupling, while $\Lambda_0/\Lambda_1 \cong 50$ for the presently anticipated " canonical " set of coupling constants [7]. Unfortunately, Λ_1 would be accessible to experiment only at very low gas pressures.

One can consider μ-absorption by H^2 or He^3 to get sufficient information to determine the coupling constants. It is not clear that wavefunctions of these nuclei are sufficiently well known to ensure that this goal could be reached even if the relevant absorption rates were readily measurable.

III. THE $(\mu\nu)(e\nu)$ INTERACTION

(a) μ^+ lifetime

This quantity has been during the last year the object of precision measurements by the Chicago, Carnegie Tech. and Liverpool groups, with the following results :

Chicago [12]	(2.208 ± 0.004) μsec
Carnegie Tech. [20]	(2.211 ± 0.003) μsec
Liverpool [21]	(2.225 ± 0.006) μsec

These values are in reasonable agreement with each other and with the old value of (2.22 ± 0.02) μsec of Bell and Hincks. The mean of the experimental values reported above appears to differ by several per cent from the theoretical value predicted, using the latest value of the vector coupling constant of beta decay and applying all radiative corrections. We refer to Feynman's report in Session S 4 for a detailed discussion of this matter.

The accuracies claimed by the various groups for their results listed above are certainly very high as compared to most lifetime determinations of ordinary nuclear beta decay. The agreement between the results obtained should therefore perhaps not be taken as the ultimate proof that they are necessarily exempt from systematic biases of unknown origin[22].

(b) ϱ value

This parameter for the decay of *negative* muons was determined, using stops in a helium bubble chamber, in a collaboration experiment between Bologna, Duke and Milano Universities [23].

4300 decay electrons were measured of which 2279 met the selection criteria used to eliminate poorly measured events without biasing the spectrum. The measured momentum of each electron was corrected for ionization and bremsstrahlung loss. A preliminary statistical analysis of 2279 electrons gave $\rho = 0.764 \pm 0.032$ where the error includes the author's estimate of the systematic error (0.21 %). This result should be considered tentative as the data seem to indicate that a systematic error, which is considerably larger than that estimated, was made in the calibration of the momentum scale.

IV. THE $(np)(\mu\nu)$ INTERACTION

(a) Redetermination of the Fermi coupling constant

The *ft*-value of O^{14} has been the subject of detailed re-investigations during the past year. Both the end-point of the decay spectrum (now quoted as (1810.6 ± 1.4) keV [24]) and the half life (now quoted as (71.1 ± 0.3) sec. [25]) were found to differ from the previously quoted values, but in such a way that the final result

$$ft(O^{14}) = (3071 \pm 16)\ \text{sec}$$

still remains close to the previously accepted value, and to those for the super allowed Fermi transitions in Al^{26*} ((3100 ± 53) sec) and Cl^{34} ((3100 ± 110) sec).

(b) Miscellaneous other experiments

The " weak magnetism " effects predicted by Gell-Mann [26] on the basis of the conserved vector current hypothesis for the beta spectra of the outer members of an isotopic spin triad have been now investigated experimentally, albeit with no conclusive result. For the $A = 12$ triad, Hilton and coworkers [27] at Cal. Tech. performed two different experiments, finding in one a null result, and in the other an effect of twice the magnitude of that predicted theoretically. The positive results for the $A = 8$ triad are as yet not readily interpretable, because the strength of the electromagnetic transition in Be^8 is so far not available from experiment.

A new type of experiment, involving the comparison of beta-gamma circular polarization correlations in the $A = 24$ multiplet, has been proposed by Bouchiat [28] as a test of " weak magnetism ".

V. " FORBIDDEN " PROCESSES

(a) $A+\mu^- \rightarrow A+e^-$

The neutrinoless conversion of a muon into an electron has recently been reinvestigated, using muons stopping in Cu, by a group at Berkeley [3] and by a group from Rome working at CERN [4]. The Berkeley group used a magnetic spectrometer set at 92 MeV to detect the expected " conversion " electrons, while the Rome group used a calibrated coincidence counter telescope for the same purpose. The " conversion " process sought could occur either coherently (without excitation of the residual nucleus *A*) or incoherently (with excitation of *A*). The Berkeley experiment, involving the selection of monochromatic electrons, could only detect the coherent process, while the CERN-Rome experiment, involving the continuous registration of a differential electron range curve, would detect both. In terms of the branching ratio, *R*, of the " conversion " process to ordinary muon capture in Cu the results of these experiments are given in Table II :

Table II

		Events observed	R	Statistics of error
Coherent	Berkeley	3	$\left(4^{+3}_{-2}\right) \times 10^{-6}$	Standard dev.
	CERN-Rome	0	$\leqslant 6.6 \times 10^{-6}$	95 % conf. level
Incoherent	CERN-Rome (*)	0	2×10^{-5}	95 % conf. level

(*) assuming a mean excitation of 20 MeV of the residual nucleus.

It must be emphasized that the Berkeley group actually *observed* 3 events which, if not attributed to the " conversion " process sought, could be explained only in terms of fluctuations in the accidentals.

The Berkeley group also briefly investigated whether the " Yovanovitch " effect (see Section VII) could not be attributed to an anomalously high production of " conversion " electrons in Fe. Substituting an Fe target for the Cu target used in their main experiment, they observed that in a time when about 55 electrons should have been registered (if the Yovanovitch effect were to be explained this way) none were found.

(b) Other effects

$\mu^+ \rightarrow 3e$

This process has been investigated by Lee and Samios [29], finding for the branching ratio with respect to the normal decay mode an upper limit of $(1\pm1)\times10^{-5}$. This process is interesting inasmuch as the same devices which can be used not to rule out the existence of the intermediate heavy vector boson (on the basis that the process $\mu\rightarrow e+\gamma$ is absent) can probably at the same time not be used to abolish this process [30].

$\mu^- + e^+ \rightarrow 2\gamma$

This possible annihilation mode of muonium was investigated by York, Kim and Kernan [31]. Such an experiment yields interesting information if one makes some plausible assumptions about the formation of muonium in the stopping material used (based on experience with positrons). An experimental lower limit of (2.5 ± 0.4) sec for the annihilation rate was found.

VI. PION DECAY

The pion lifetime has been redetermined by Ashkin et al [32], with the result $\tau(\pi^+) = (25.46\pm0.32)$ ns. As a by-product of their work on π-e decay, Anderson et al [33] obtained the value $\tau(\pi^+) = (25.6\pm0.8)$ ns. Fig. 13, essentially taken over from Ashkin et al [32], (with point (9) from ref. [33]) summarizes our present knowledge of $\tau(\mu^+)$.

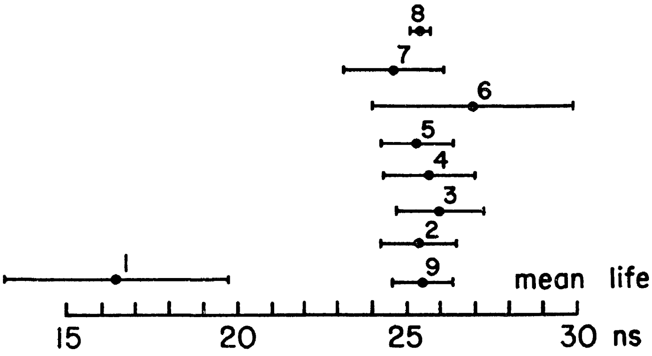

Fig. 13 Summary of all existing π-lifetime data.

The work of Anderson et al, although reported at Kiev last year, is now available in definitive form. The observed branching ratio

$$R_{\exp}\left(\frac{\pi\rightarrow e}{\pi\rightarrow\mu}\right) = (1.21\pm0.07)\times10^{-4}$$

is in good agreement with the theoretical value

$$R_{\mathrm{th}}\left(\frac{\pi\rightarrow e}{\pi\rightarrow\mu}\right) = 1.23\times10^{-4}$$

calculated for pure A-interaction and corrected for radiation effects. It must be emphasized once again that this close agreement is our best evidence to date that the GT-couplings in beta decay and μ-capture are both A and essentially of the same strengths. They appear to have, within experimental error, the same strength at 4-momentum transfer q equal to the pion rest mass m_π (whereas one normally compares β-decay $q\approx0$ and μ-capture at $q\approx m_\mu$).

A Rumanian group [34] has continued their investigation of the spatial properties of π-μ decay. They used (307 ± 10) MeV π^+ from the reaction $p+p\rightarrow d+\pi^+$, and state on the basis of 17,321 complete π-μ-e decays at rest that the anisotropy earlier reported by them persists, in spite of careful checks for systematic errors. In terms of the *projected* angle ϕ with respect to the pion beam direction they obtain with a distribution

$$f(\phi) = (1+\beta\cos\phi+\gamma\cos^2\phi)d\phi$$

a better fit $(P_{\chi 2}\sim 2\times10^{-3})$ than with the assumption $\gamma=0$ $(P_{\chi 2}\ll10^{-5})$ or of isotropy $(P_{\chi 2}\ll10^{-5})$. Disagreement with the results of earlier workers is attributed *(a)* to their lack of sufficient statistics and *(b)* to the different pion beams used by these workers.

No effects attributable to transverse polarization are found by the Rumanian group. They attribute their results to longitudinally polarized " pions " with spin $J \neq 0$; the required presence of higher powers of ϕ than $\cos^2 \phi$ would require $J > 1$.

This interesting contribution, which certainly deserves critical evaluation, reached the rapporteur too late to enable him to reach his own conclusions.

VII. NON-WEAK PROPERTIES OF THE MUON

(a) Mass and magnetic moment

Two independent measurements, both using the critical absorption of the $3D \rightarrow 2P$ transition in the μ-mesic P-atom, have appeared in 1960. The first of these (I) used NaI as a detector, the second (II) a Xe-filled proportional counter. The results were

$$\mathrm{I} : m_\mu = (206.74 \pm^{0.03}_{0.04}) m_e$$ [35, 45]

$$\mathrm{II} : m_\mu = (206.76 \pm^{0.02}_{0.03}) m_e$$ [36]

while the mass value predicted from quantum electrodynamics and the magnetic moment measured by a Columbia group [37] is

$$m_\mu(\mathrm{QED}) = (206.77 \pm 0.013) m_e .$$

The anomaly, $(g_\mu/2-1)$, computed from the Columbia frequency measurement [37] and II is

$$(g_\mu/2-1) = (1.13 \pm^{0,12}_{0,17}) \times 10^{-3} .$$

Electric dipole moment (EDM) of the muon

Using equipment designed essentially for a measurement of $(g/2-1)$, a CERN group [38] has obtained a new lower limit for this quantity, viz

$$(\mathrm{EDM})(\mu^+) < e(5 \pm 5) \times 10^{-17} \text{ cm}.$$

As is well known, a violation of time reversal symmetry would be a necessary condition for EDM $\neq 0$.

(b) Depolarization

It is well known that negative muons suffer a great deal of depolarization when brought to rest. For spin-zero nuclei, this is mostly attributed to the spin-orbit coupling in the orbits of the mesic atom; for nuclei with finite spin, there is an additional depolarization by the muon-nucleus interaction. In addition to these effects, there may be a depolarization due to a coupling between the μ^- and unsaturated electron spins (" paramagnetism "). A Dubna group [39] has now obtained evidence for this latter mechanism. They find that while Pd depolarizes completely ($a < 0.01$), Pd-hydride $\mathrm{PdH}_{0.6}$ gives $a \sim -0.045 \pm 0.01$. Cr, W and Mo all give essentially zero asymmetry. All these elements have predominantly even-even isotopes with zero spin.

Both the spin-orbit interaction and the nuclear h.f. coupling are too strong to be decoupled by fields readily attainable in the laboratory. A Rumanian group [40] have investigated, in fields of 150 and 10^4 gauss respectively, the asymmetry parameter a for $\mu^- - e^-$ decays from π's stopped in nuclear emulsion. They report

$$\mathrm{H} = 150 \text{ gauss} \qquad a_- = -(2.5 \pm 2.8) \times 10^{-2}$$

$$\mathrm{H} = 10^4 \text{ gauss} \qquad a_- = -(11 \pm 2.8) \times 10^{-2} .$$

Rose's prediction of depolarization by coupling between electron cloud and μ^- is supposedly confirmed by their experimental observation.

(c) Radiationless $2p$—$1s$ transitions in μ-mesic atoms

In continuation of work presented last year at Kiev, a Dubna group [41] has continued to study the deficiency of K X-rays in the heaviest mesic atoms (Th, Bi, U). This deficiency is now, although the measurements were done with rather poor resolution, well established for U, with a difference for U^{235} and U^{238}. The " conversion " could take place by one of three channels: *(a)* fission, *(b)* neutron emission, and *(c)* nuclear excitation followed by gamma emission (" Raman effect "). Indirect arguments of the Russian group, based on threshold energy considerations, point to mechanism *(c)*. This is supported by direct observation at Chicago [42] that no prompt neutron emission from muons in either isotope of U is seen. The *shape* of the mesic K-ray " lines ", taken with good resolution in Chicago, varies greatly from one isotope to the other, thus lending support to the hypothesis of a quadrupole excitation of low-energy nuclear levels.

(d) Yovanovitch effect in μ- decay

Yovanovitch [43] has firmly established that the bound μ^- *decay* rate $\Lambda_d(Z)$, differs, presumably through effects of atomic binding, from the vacuum decay rate $\Lambda_d(0)$. For $Z > 30$, $R = \Lambda_d(Z)/\Lambda_d(0) < 1$, as one would predict from elementary arguments. In the range $20 < Z < 30$, $R > 1$, and in particular exhibits for Fe a peak value $R = 1.15$. No reasonable theoretical explanation has so far been advanced for either the magnitude of this " speeding up " of the decay and yet less for its sharp Z-dependence.

In Yovanovitch's measurements, precautions were taken so that nuclear γ-rays of energy $E_\gamma \leq 10$ MeV would be counted with $< 10^{-3}$ efficiency. An increase in the number of decay electrons could thus only be simulated by photons with $E_\gamma > 10$ MeV. Keuffel has presented preliminary evidence at this Conference [44] that, at least in Fe, γ-rays up to 20 MeV are emitted in fair numbers. To explain the Yovanovitch effect, it remains to be proved that these γ-rays (which present a mystery from the nuclear physics point of view) are absent in Cu.

It is a pleasure for the rapporteur to thank Prof. H. Primakoff for many enlightening discussions during the preparation of this report.

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DISCUSSION

BERNSTEIN: It has been pointed out by you and other people that the rate R is, in principle, measurable directly from the time variation of the asymmetry of electrons in μ decay. What is the experimental status of the measurement?

TELEGDI: We are discussing a diagram in which there is one unknown quantity. Bernstein points out that this could be measured. Assume that you have something like P with spin $\frac{1}{2}$. In the $F = 1$ state the muon precesses, but in the $F = 0$ state it does not. When it converts from the upper hyperfine state, the precession amplitude decays. The decay rate thus indicates the conversion rate. All I can say is that Ignatenko and his group in Russia have found that in P μ-mesons get depolarized twice as much as they do in C. (This is just what you would expect for a spin $\frac{1}{2}$ nucleus.) The Chicago group has looked at the precession of muons in P and find no asymmetry at all. When there is no asymmetry, we cannot see the precession; perhaps this means the conversion is very rapid. The Russian experiment has appeared in print, and therefore I consider it more trustworthy than ours, which we have done only once. It is quite clear that this question should be settled by direct measurement of the conversion rate. But let us hope that the hydrogen experiment will be done first.