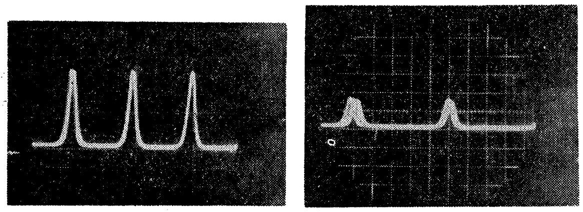


(a) (b)

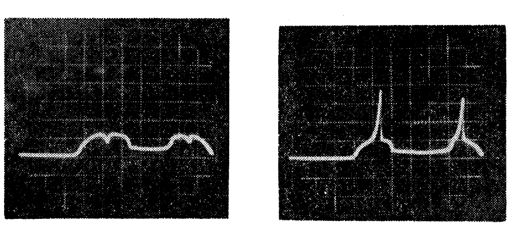
FIG. 1. X-band (9.22 kMc/sec) pulses emitted by ruby under constant H, fixed pumping frequency, and no external X-band signal. Figure 1(a) shows that the pulse interval is about 0.3 msec corresponding to maximum power available. Figure 1(b) shows the effect of reduced pumping power.

above frequencies. A ruby crystal, with about 0.1% chromium concentration, was placed at the center of the cavity on the end of an axially located quartz rod. The crystal was mounted so as to make the c axis normal to the cavity axis. A selected Varian VA-96 klystron, rated at 120 mw, was used for pumping.

At room temperature, K- and X-band absorption lines characteristic to ruby were observed, and no interaction of any kind between the two bands was detected. The initial evidence of stimulated microwave emission in ruby was obtained at liquid helium temperature (4.2°K), with a sample of about three cubic millimeters in volume. Subsequently, the volume of the sample was increased to approximately two tenths of a cubic centimeter. Evidence of oscillations and amplification was obtained with the latter sample.

Figures 1(a) and 1(b) demonstrate the dependence of emitted X-band power on pumping power in the absence of an external X-band signal. It is interesting to note that both the pulse-height and the repetition rate decrease with decreased pumping power. The pulse interval was found to be approximately 0.3 millisecond for maximum K-band power at our disposal. The radiated frequency was 9.22 kMc/sec for $H=4230$ gauss and pumping frequency of 24.2 kMc/sec.

Figures 2(a) and 2(b) show the effects of amplification. The traces were taken before and after application of K-band power, respectively. The small downward pips in Fig. 2(a) indicate the position of cavity resonance. Net gain up to 20 db has been observed. For this presentation, a small frequency-modulated X-band signal was applied to the cavity.



(a) (b)

FIG. 2. The traces (a) and (b) were obtained before and after application of pumping power, respectively, which was maintained below oscillation level. To observe amplification, a small frequency-modulated X-band signal was applied to the cavity.

Details of this study will be published at a later date. In the meantime we should like to point out that ruby possesses a number of physical properties which contribute to its usefulness as a maser medium, such as very high chemical stability, good thermal conductivity, and low dielectric losses.

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Decay of the π Meson and a Universal Fermi Interaction

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It is well known that π mesons rarely decay into electrons, with or without the emission of a γ ray. Experimental upper limits for the frequencies of such decay modes as compared to the more usual π-μ decay are[1]

$$\rho=(\pi\rightarrow e+\nu)/(\pi\rightarrow\mu+\nu)<10^{-5}, \quad (1)$$

$$\rho_\gamma=(\pi\rightarrow e+\gamma+\nu)/(\pi\rightarrow\mu+\nu)<10^{-5}. \quad (2)$$

Based upon the values of the coupling constants in nuclear β decay as accepted a few years ago, various workers[2] have expressed the belief that the smallness of (1) and (2) cannot be understood in terms of a universal Fermi interaction. The purpose of this note is to point out that this belief is no longer necessary in the light of recent experiments in nuclear β decay. On the contrary, in the framework of a universal Fermi interaction, the conditions (1) and (2) determine a set of universal coupling constants which is not ruled out by existing experiments. Such a set will be exhibited below. The calculations leading to these results are similar to those made by Treiman and Wyld,[2] and some of the results have already been obtained by them. In the following, we employ units in which $\hbar=c=m_\pi=1$, where m_π is the mass of the π meson. We state the results as follows.

1. The decay modes $\pi\to\mu+\nu$ and $\pi\to e+\nu$ are assumed to take place via the weak μ and e decays of virtual nucleons, into which the π dissociates. A universal Fermi interaction is assumed, so that these weak decays share the same set of coupling constants[3] C_S, C_V, C_A, C_T, C_P; and, as usual these weak interactions are taken into account only to first order. The matrix elements here concerned depend only on C_A and C_P, by selection rules:

$$\mathfrak{M}=(\bar{u}(p)\Gamma v(p_\nu)), \tag{3}$$

where

$$\Gamma=\gamma_5(C_P f_P - C_A f_A m), \tag{4}$$

and where $u(p)$ is the spinor of either μ or e (of four-momentum p and mass m), and $v(p_\nu)$ is the spinor of the neutrino. The numbers f_P, f_A are the same for both μ and e decay modes. Condition (1) requires (4) to be small for electrons. Requiring it to be exactly zero for electrons yields the condition

$$C_P/C_A=m_e f_A/f_P. \tag{5}$$

An estimate of f_A, f_P based on a cutoff perturbation calculation of the π-nuclear interaction gives, with a cutoff equal to the nucleon mass,

$$f_A/f_P\sim 1/M. \tag{6}$$

If this estimate is adopted, then (5) requires

$$C_P/C_A\sim m_e/M\sim 10^{-3}. \tag{7}$$

This number is essentially deduced from our assumption of a universal Fermi interaction and experiment. We have no explanation at this time for the appearance of such a small number. The values of C_S, C_V, C_T are here undetermined.

2. The matrix elements for the radiative decays $\pi\to\mu+\gamma+\nu$ or $\pi\to e+\gamma+\nu$ involve all the Fermi coupling constants except C_S, which is ruled out by selection rules. The requirement of gauge invariance leads to the following form for the matrix elements:

$$\mathfrak{M}'=(\bar{u}(p)\Gamma' v(p_\nu)), \tag{8}$$

where

$$\Gamma'=\gamma_5\{(C_P f_P - mC_A f_A)[\boldsymbol{\varepsilon}(q-im)/2(p\cdot k)] + (C_A G_A + C_V G_V)(k\cdot q)\boldsymbol{\varepsilon} + C_T G_T \boldsymbol{\varepsilon}\mathbf{k}\}, \tag{9}$$

where ϵ, k are, respectively, the polarization and momentum four-vector of the photon, q is the momentum four-vector of the π meson, $(q\cdot k)$ denotes the four-vector scalar product, $\boldsymbol{\varepsilon}=\gamma_\mu\epsilon_\mu$, and $\mathbf{k}=\gamma_\mu k_\mu$. In formula (9) the special gauge in which $(\epsilon\cdot q)=0$ has been adopted. The constants f_P, f_A in (9) are the same ones that appear in (4). The numbers G_A, G_V, G_T are functions of M and $(q\cdot k)$. An estimate based on a cutoff perturbation calculation in the π-nuclear interaction gives

$$G_A/f_A\sim G_V/f_A\sim 1/M^2;\quad G_T/f_A\sim 1/M. \tag{10}$$

For $\pi\to e+\gamma+\nu$, the first term of (9) vanishes by (5). If one puts $C_T=0$, then only the second term of (8) remains. If further $C_V\lesssim C_A$, then it yields the ratio

$$\rho_\gamma\sim 10^{-8}, \tag{11}$$

as obtained earlier by Treiman and Wyld. Condition (2) is thus satisfied. The smallness of this ratio is independent of the mass of e. Thus, the rarity of $\pi\to e+\gamma+\nu$ is a consequence of the rarity of $\pi\to e+\nu$. It should be noted that the smallness of ρ_γ does not depend critically on $C_T=0$. As long as $C_T/C_A\lesssim 1$, one obtains ρ_γ consistent with (2).

3. One may propose the following set of universal coupling constants[4]:

$$C_V/C_A\sim 1;\quad C_P/C_A\sim m_e/M;\quad C_S=C_T=0. \tag{12}$$

This is consistent with (1), (2), and is consistent with all existing experiments in nuclear β decay in which parity nonconservation is observed.[5,6] The results of existing recoil experiments in nuclear β decay[5] however, are mutually contradictory, if any model of local Fermi interactions is adopted. These data therefore neither confirm nor contradict (12). It may be remarked, however, that (12) can be consistent with existing recoil experiments if the experiment on He^6 is ignored.

4. Experimental results of the π-μ-e decay sequence do not pose as tests for (12), because the choice of a Hamiltonian for the μ-e decay interaction is not unique.

5. Adopting the set of coupling constants (12), one can calculate the ratio of the respective cross sections for radiative and nonradiative π-μ decay. Only the part proportional to C_A in the first term of (9) need be retained for this purpose, and one obtains a result that is independent of any undetermined constants:

$$(\pi\to\mu+\gamma+\nu)/(\pi\to\mu+\nu) \cong 1.1\times 10^{-4}\ln(\omega_{\max}/\omega_{\min}). \tag{13}$$

Taking into account all photons between 1 Mev and the maximum energy of 28 Mev, one obtains 3.7×10^{-4}. This number is to be compared with the observed relative frequency of "anomalous" to normal π-μ decay $(3.3\pm 1.3)\times 10^{-4}$.[7]

6. The previous developments, in particular the estimates (10), depend on the assumption that the $\pi\to\mu+\nu$, $\pi\to e+\nu$ decay mechanisms involve high-energy intermediate states, with a characteristic energy of the order of M. Therefore, an accurate measurement of the γ spectrum from $\pi\to\mu+\gamma+\nu$ would be of considerable interest, since it effectively measures this characteristic energy. It may be seen from (9) and (4) that the spectrum predicted by the first term in (9) is independent of the mechanism of π decay, and is in fact equivalent to what one would obtain from a local $\pi\to\mu+\nu$ interaction. The remaining terms, however, are model-dependent, and in fact indicate a current carrying intermediate state which in turn decays into the $\mu+\nu$ pair. A measurement of the spectrum of

sufficient accuracy to measure the deviation of the matrix element from the first term of (9) would therefore give us information about the $\pi\rightarrow\mu+\nu$ decay mechanism. This accuracy must be $\sim 1/M$ if $C_T\approx C_A$, or $\sim 1/M^2$ if $C_T\approx 0$.

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Refraction Effects in Direct Nuclear Reactions

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For all bombarding energies in the range 11.8 Mev–96 Mev, the observed angular distributions[1] for the reaction $C^{12}(p,p')C^{12*}$ ($Q=-4.4$ Mev) rise to peaks as the scattering angle approaches $\theta=0°$. Nevertheless this reaction appears to proceed as a direct interaction with angular momentum transfer $l=2$. Elementary theories[2] then all predict that the cross section should be small near $\theta=0°$, rising to appreciable values only at angles approaching those at which $qR=l=2$. Here R is the nuclear radius, and $\mathbf{q}=\mathbf{k}_i-\mathbf{k}_f$ is the difference between the incident and outgoing momenta. The magnitude of $\mathbf{q}$ always increases as $\mathbf{k}_f$ rotates towards larger angles, and for most experiments is quite small when $\theta=0°$. It is clear that the experiments are in striking disagreement with the predictions of the simple theory.

A more sophisticated calculation has been performed by Levinson and Banerjee,[3] treating the same direct-reaction mechanism, but going beyond the use of free-wave functions for the incoming and outgoing particles. Their wave functions are eigenfunctions of an optical potential. It is very interesting that these authors have been able to demonstrate an optical potential which

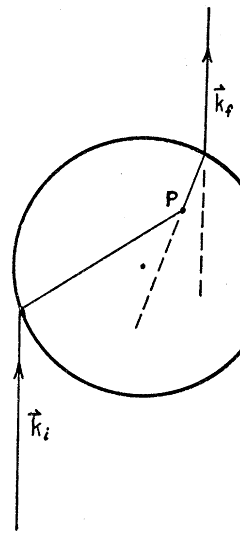

FIG. 1. Mechanism of production of the forward refracted peak in a direct inelastic reaction. Note that each ray is refracted at the nuclear surface in such a way that angular momentum is conserved. The actual change in angular momentum of the nucleus occurs at the point P.

permits reasonable fits to the entire range of the $C^{12}(p,p')$ data. The peak at $\theta=0°$ seems to be a particularly straightforward consequence of their work, appearing for a variety of potential types. We wish to indicate here that one can understand in a simple way why deviations from the elementary theory[2] should be most important near $\theta=0°$, and why these deviations then are such as to produce quite large cross sections.

From a semiclassical point of view, and assuming undeviated motion of the incident and outgoing particles through the nucleus, the linear momentum transfer $\mathbf{q}$ corresponds to an angular momentum transfer $|\mathbf{q}\times\mathbf{r}|$, where the reaction which produces the outgoing particle is assumed to be local and to take place at the point $\mathbf{r}$. A definite inelastic reaction requires a definite angular momentum transfer,

$$l=|\mathbf{q}\times\mathbf{r}|,$$

limiting the values of $\mathbf{r}$ at which the reaction can proceed. This is the origin of the selection rule which establishes the location of the first peak of the angular distribution. The minimum possible value of q is that for which $l=qR$, for $r>R$ gives no reaction.

When one considers that particles i and f can travel along rays which might be refracted at the nuclear surface, it is seen that $qR<l$ at $\theta=0°$ no longer need imply a small cross section. Examination of Fig. 1 shows that the refraction at the surface of an optical potential, in combination with a direct reaction in the interior, is able to produce an outgoing ray which while parallel to the incoming ray nevertheless has a quite different impact parameter. Thus the necessary angular momentum transfer is achieved, and the cross section will peak at $\theta=0°$. Naturally, this effect is enhanced by the fact that the basic interaction in any direct process always is strongest for small q.

Most of the rays which contribute for scattering angles much greater than $\theta=0°$ have the property that