PHYSICAL REVIEW VOLUME 126, NUMBER 2 APRIL 15, 1962

Neutrino-Induced Reaction in C^{12}†

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(Received December 7, 1961)

The reaction with C^{12}, leading to the ground state of N^{12}, of neutrinos from stopped pion and muon sources has been suggested as a possible means for proving the identity of "muon" and "electron" neutrinos. The cross section and angular distribution of this reaction are investigated here, and the total reaction probability is shown to be reduced by nuclear structure effects below the free-nucleon value. Other possible targets for the neutrino-induced reaction are mentioned.

I. INTRODUCTION

NEUTRINO-INDUCED reactions are capable in principle—and provided sufficiently intense neutrino beams can be made available, also in practice—of providing us with much new insight into questions of weak-interaction theory which sometimes could not be obtained otherwise. Two such problems, soluble with high-energy neutrino beams only, would be the hypothetical intermediate boson transmitting the weak interactions, whose existence could be shown by having the neutrinos produce it, and, secondly, the question of form factors of the weak interaction. Neutrino beams with only intermediate energy ($\lesssim$300 Mev) could already prove the presence of a coupling leading to neutrino-lepton scattering; and most important, they could answer the fundamental problem of a possible identity of ν_e ("electron neutrino") and ν_μ ("muon neutrino") if one tries to obtain electrons in reactions induced by ν_μ. Pontecorvo[1] has recently pointed out that the use of neutrinos given off by stopped pions or muons may in this connection be of some advantage: Although the cross sections are smaller at low energies, these neutrinos could be produced with higher intensities, and, most of all, they have well-defined energies which facilitates the identification of the events. Stopped π^+ mesons give off a ν_μ with 29.9 Mev energy; μ^- mesons captured in a nucleus generate a ν_μ with a fairly narrow energy spectrum[2] concentrated around 90 Mev. Using these neutrinos, a possible reaction

$$\nu_\mu + n \rightarrow p + e^-, \tag{1}$$

may then be looked for. Decay of the μ^+ from the π^+ could provide a disturbing background of ν_e's with energies[2] up to 53 Mev.

In place of (1), it was suggested[1] to look for the reaction

$$\nu_\mu + C^{12} \rightarrow N^{12} + e^-, \tag{2}$$

leading to the ground state of N^{12}, which besides the well-defined energy of e^- provides us with an additional identifying signal given by the delayed positron in the subsequent decay,

$$N^{12} \rightarrow C^{12} + e^+ + \nu_e. \tag{3}$$

In the following, we present a fairly rough estimate of the cross section and angular distribution of the reaction (2), based on a shell-model calculation as well as on a comparison with the empirical beta decay rate of (3). It will be shown that the maximum of the rate of (2) occurs at neutrino energies $\sim$85 Mev, so that μ-capture neutrinos would be suitable. However, this maximum rate is reduced considerably below the rate of the reaction (1) at this energy by nuclear structure effects, so that the feasibility of Pontecorvo's proposal becomes less obvious. Finally, we shall discuss orders of magnitude of reactions similar to (2) with different targets.

II. EVALUATION

If we call $\mathbf{v}$ the neutrino momentum, $\mathbf{p}$ and E the electron momentum and energy, and m its mass, Δ the $N^{12}-C^{12}$ mass difference (being[3] $\Delta = 17.7$ Mev), and $\mathbf{P}$ the N^{12} recoil momentum, then the kinematics of reaction (2) is

$$\begin{aligned} \mathbf{v} &= \mathbf{p} + \mathbf{P}, \\ \nu &\cong \Delta + E, \end{aligned} \tag{4}$$

and the neutrino threshold is given by

$$\nu \geqslant \Delta + m = 18.2 \text{ Mev}. \tag{5}$$

We shall always consider energies well above the threshold, i.e., neglect the electron mass. The positron in the N^{12} decay is emitted at 16.6 Mev, with a half-life $t_{\frac{1}{2}} = 0.0125$ sec, and the ft value,[3] $\log ft_{\frac{1}{2}} = 4.18$, is that of an unfavored allowed transition. We conclude that (3) is a Gamow-Teller transition, corresponding to a spin $J=1$ of the N^{12} ground state. Thus, for reaction (1), a Hamiltonian

$$H = g_G\left(\phi_p{}^\dagger \psi_e{}^\dagger \boldsymbol{\sigma}\cdot\boldsymbol{\sigma}^N \frac{1+\gamma_5}{\sqrt{2}} \psi_\nu \phi_n\right), \tag{6}$$

will be used, as it can be shown that for a $J=0 \leftrightarrow J=1$ transition, the Fermi matrix elements vanish not only in beta decay, but even when they contain a retardation

† Work supported in part by the Office of Naval Research, United States Navy.

[1] B. Pontecorvo, *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester* (Interscience Publishers, Inc., New York, 1960), p. 617.

[2] H. Überall, Nuovo cimento (to be published).

[3] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **27**, 77 (1955).

factor,[4] as in the $\nu - e$ reaction. Form factors and relativistic terms are left out in (6)—they will not be larger than $\sim 10\%$ at the neutrino energies considered—and so is the induced pseudoscalar[5] which is vanishingly small if the charged lepton is an electron. The coupling constant is taken as $g_G = 1.21 g_F$; $g_F = 10^{-5} m_p^{-2}$; m_p = proton mass. We find for the cross section of reaction (2):

$$d\sigma = \frac{p^2}{\pi}\frac{d\Omega}{4\pi} g_G^2 \sum_M \{2\,\mathrm{Re}(\mathbf{v}/\nu)\cdot\mathfrak{M}^*(\mathbf{P})\hat{p}\cdot\mathfrak{M}(\mathbf{P}) + (1-\mathbf{v}\cdot\hat{p}/\nu)|\mathfrak{M}(\mathbf{P})|^2 + i(\hat{p}-\mathbf{v}/\nu)\cdot[\mathfrak{M}^*(\mathbf{P})\times\mathfrak{M}(\mathbf{P})]\}, \quad (7)$$

with $d\Omega$ the solid angle over directions of $\mathbf{p}$, M the magnetic quantum number of the N^{12} spin, $\hat{p} = \mathbf{p}/p$, and a matrix element

$$\mathfrak{M}(\mathbf{P}) = \langle \Phi_N^\dagger \textstyle\sum_i \tau_i^+ \boldsymbol{\sigma}^i e^{i\mathbf{P}\cdot\mathbf{r}_i}\Phi_C\rangle. \quad (8)$$

The same matrix element is contained in the beta decay (3),

$$\frac{\ln 2}{ft_{\frac{1}{2}}} = \frac{g_G^2}{2\pi^3}\frac{1}{3}\sum_M |\mathfrak{M}(0)|^2, \quad (9)$$

for zero momentum transfer. A calculation of (8) using the shell model is bound to be uncertain, due to unknown radii of the shells in the radial overlap integrals, and to mixed configurations. We therefore take $|\mathfrak{M}(0)|^2$ from (9) using the experimental ft value, and shall only attempt to calculate the *ratio* of $\mathfrak{M}(\mathbf{P})$ and $\mathfrak{M}(0)$ with a very simple shell model with unmixed configurations:

$$\begin{aligned}&(1s_{\frac{1}{2}}^2)_p\,(1s_{\frac{1}{2}}^2)_n\,(1p_{\frac{3}{2}}^4)_p\,(1p_{\frac{3}{2}}^4)_n, \quad \text{for}\quad C^{12},\\ &(1s_{\frac{1}{2}}^2)_p\,(1s_{\frac{1}{2}}^2)_n\,(1p_{\frac{3}{2}}^4)_p\,(1p_{\frac{3}{2}}^3)_n\,(1p_{\frac{1}{2}}^1)_p, \quad J=1, \quad \text{for}\quad N^{12};\end{aligned} \quad (10)$$

in the p-shell radial wave function (taken the same for $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$, and for both C^{12} and N^{12}),

$$R_{11} = 2\alpha^2(2\alpha)^{\frac{1}{2}}3^{-\frac{1}{2}}\pi^{-\frac{1}{4}} r e^{-\frac{1}{2}\alpha^2 r^2}, \quad (11)$$

we use $\alpha^{-1} = 1.6\times10^{-13}$ cm corresponding to the C^{12} rms radius[6] of 2.5×10^{-13} cm. This procedure leads to

$$\mathfrak{M}(\mathbf{P}) \propto \langle [X_{\frac{3}{2}}^n(123)\varphi_{\frac{1}{2}}^p(4)]_{J=1}^\dagger e^{i\mathbf{P}\cdot\mathbf{r}_4}\boldsymbol{\sigma}^4\tau_4^+\Phi_{\frac{3}{2}}^n(1234)\rangle, \quad (12)$$

and we obtain a cross section

$$d\sigma = \frac{p^2}{\pi}\frac{d\Omega}{4\pi} g_G^2 (1-\tfrac{1}{3}\mathbf{v}\cdot\hat{p}/\nu)\sum_M |\mathfrak{M}(\mathbf{P})|^2, \quad (13)$$

where finally

$$\sum_M |\mathfrak{M}(\mathbf{P})|^2 = \sum_M |\mathfrak{M}(0)|^2 \left(1-\frac{P^2}{4\alpha^2}\right) e^{-P^2/2\alpha^2}. \quad (14)$$

[4] A. Fujii and H. Primakoff, Nuovo cimento **12**, 327 (1959).
[5] M. L. Goldberger and S. B. Treiman, Phys. Rev. **111**, 355 (1959).
[6] R. Hofstadter, Ann. Rev. Nuclear Sci. **7**, 231 (1957).

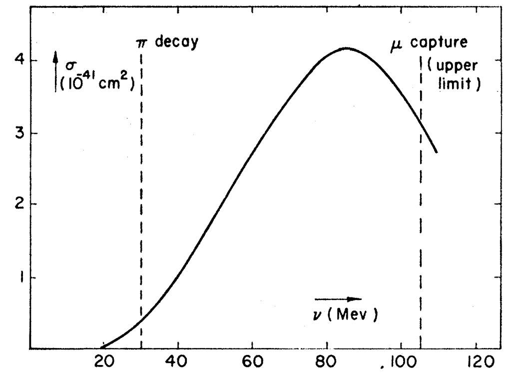

FIG. 1. Cross section of $\nu + C^{12} \rightarrow N^{12} + e^-$, vs neutrino energy.

Equation (9) gives

$$\tfrac{1}{3}\sum_M |\mathfrak{M}(0)|^2 = 0.29, \quad (15)$$

a fairly small value indicating incomplete overlap and/or mixed configurations. Integration of (13) over $d\Omega$ gives

$$\sigma(\nu) = 0.29\frac{g_G^2}{4\pi}\frac{\alpha^4}{\nu^2}[1+y-(1+2y-\tfrac{3}{2}y^2+y^3)e^{-y}], \quad (16)$$

where

$$y = (\nu+p)^2/2\alpha^2, \quad (17)$$

and where the approximation $(2\nu-\Delta)^2 \gg \Delta^2$ has been made, requiring $\nu \gtrsim 30$ Mev. This cross section is shown in Fig. 1, together with the neutrino energies from π^+ decay and from μ^- capture (upper limit). It has a maximum at $\nu \sim 85$ Mev, indicating that neutrinos from muon capture should be used in reaction (2). Unfortunately, the maximum is only $\sigma_{\max} \sim 4\times10^{-41}$ cm^2, considerably smaller than the value[7] $\sigma \sim 5\times10^{-40}$ cm^2 for reaction (1). This is due not only to the absence of the Fermi interaction which participates in (1), but much more to the smallness of (15), or the largeness of ft. This cir-

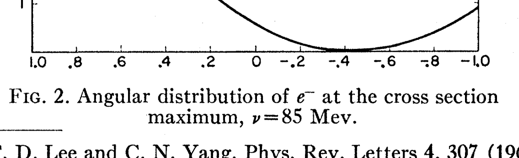

FIG. 2. Angular distribution of e^- at the cross section maximum, $\nu = 85$ Mev.

[7] T. D. Lee and C. N. Yang, Phys. Rev. Letters **4**, 307 (1960); N. Cabibbo and R. Gatto, Nuovo cimento **15**, 304 (1960).

TABLE I. Possible targets for neutrino reactions.

Target	Product	e^+ decay of product $\log ft$	$t_{\frac{1}{2}}$(sec)	σ_{max}(cm^2)	ν_{max} (Mev)
C^{12}	N^{12}	4.18	0.0125	4×10^{-41}	85
Al^{27}	Si^{27}	3.6	3.7	2.5×10^{-40}	66
P^{31}	S^{31}	3.6	2.9	2.5×10^{-40}	63
Cl^{35}	A^{35}	3.5	2.2	3×10^{-40}	61
K^{39}	Ca^{39}	3.6	1.0	2.5×10^{-40}	58

cumstance reduces considerably the prospects for a measurement of reaction (2).

The angular distribution, given by Eqs. (13) and (14), is plotted in arbitrary units in Fig. 2 for $\nu=85$ Mev, vs $\cos\theta=\hat{p}\cdot\mathbf{v}/\nu$.

III. DISCUSSION

Reaction (2), due to the identifying features of a well-defined energy of e^- (if monochromatic neutrinos are used), and a subsequent e^+ decay of the product nucleus, offered an attractive possibility for investigating the identity of ν_μ and ν_e. The smallness of the cross section is a less favorable aspect. One could ask whether other targets could be used instead of C^{12} in reaction (2), with similar features, and whose cross section could be larger due to a smaller ft value in the positron decay. Several elements are possible, and in Table I, we have chosen those which give rise to a product nucleus decaying back to the ground state of the target in no longer than several seconds and with smaller ft values. Very roughly, we have also estimated the maximum cross section for the neutrino-induced reaction (from the ratio of the ft values) and the neutrino energy corresponding to this maximum (from $\nu R\sim$const). One sees that somewhat larger cross sections might actually be obtained in this way; the subsequent decays, however, are quite slow in all cases.

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Production and Spin of the K^* Resonance*

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(Received November 10, 1961)

The experimental results of Alston *et al.* on the production of K^* in the reaction $K^-+p\rightarrow\bar{K}^0+\pi^-+p$ are discussed. If one assumes spin 1 for K^* a satisfactory explanation of the data is obtained using a model in which in addition to the exchange of a π meson the effect of the resonance Y_4^* ($m_4=1812$ Mev, $T=0$) is taken into account. This model requires Y_4^* to occur in the $d_{\frac{3}{2}}$ state of the K^-p system. We make the prediction $\langle\cos^2\theta\rangle=0.29$ in $K^-+p\rightarrow K^-+\pi^++n$. It is suggested that the measurement of a certain angular correlation at a higher energy might distinguish between $S=0$ and $S=1$ for K^*.

IN this paper we examine the production of the K^* resonance in the reactions:

$$K^-+p\rightarrow K^{*-}+p \quad (A)$$
$$\searrow \bar{K}^0+\pi^- \quad (A')$$
$$\searrow K^-+\pi^0, \quad (A'')$$
$$K^-+p\rightarrow \bar{K}^{*0}+n \quad (B)$$
$$\searrow K^-+\pi^+, \quad (B')$$

as related, in particular, to the question of the K^* spin. Our analysis is based on measurements by Alston *et al.*,[1] with incident K^- of momentum 1.15 Gev/c. We first give a summary of their results:

(1) The resonance energy is 885 Mev with a full width of 16 Mev.

(2) The branching ratio,

$$R=(K^{*-}\rightarrow K^-+\pi^0)/(K^{*-}\rightarrow\bar{K}^0+\pi^-)=0.75\pm0.35,$$

strongly favors isotopic spin $T=\frac{1}{2}$ for K^*.

(3) The branching ratio for reactions (A′) and (B′) is about one. If $T=\frac{1}{2}$, this branching ratio is the same as for the reactions (A) and (B).

(4) The total cross section for $\bar{K}^0\pi^-$ production is (2.0±0.3) mb. From a total number of 48 $\bar{K}^0\pi^-$ events, 21 have been classified as coming from an intermediate K^*. Hence, the cross section for reaction (A), assuming $T=\frac{1}{2}$, is (1.31±0.35) mb.

(5) The proton angular distribution is roughly isotropic.

(6) Let $\boldsymbol{\theta}$ be the angle between the direction of the outgoing $\bar{K}^0$ in the K^* rest system and the direction of the incoming K^-. The mean value of $\cos^2\boldsymbol{\theta}$ is 0.275. If K^* has spin zero, one should obtain $\langle\cos^2\boldsymbol{\theta}\rangle=\frac{1}{3}$, with a standard deviation of ±0.066. For spin one, the value of $\langle\cos^2\boldsymbol{\theta}\rangle$ could range from 0.2 to 0.6. Under certain plausible assumptions higher spins can be excluded.

* Work partially supported by the Conselho Nacional de Pesquisas.

[1] M. Alston, L. W. Alvarez, P. Eberhard, M. L. Good, W. Graziano, H. K. Ticho, and S. G. Wojcicki, Phys. Rev. Letters 6, 300 (1961).