TITLE: COMPETITION FROM THE $\nu_e^{208}\text{Pb} + 208\text{Bi} e^- \text{ reaction in a search for } \bar{\nu}_\mu + \bar{\nu}_e \text{ oscillation}$

AUTHOR(S): J. W. Toevs
H. W. Kruse

SUBMITTED TO: Transactions of Nuclear and Particle Physics
LAMPF, January 1981

MASTER
Competition from the $\nu_e \, ^{208}\text{Pb} \rightarrow ^{208}\text{Bi} \, e^-$

Reaction in a Search for

$\bar{\nu}_\mu + \bar{\nu}_e$ Oscillation*

by

J.W. Toews** and H.W. Kruse
Los Alamos National Laboratory

ABSTRACT

Inverse beta-decay reactions produced by electron neutrinos may compete with muon neutrino reactions in experiments utilizing the neutrino flux from a beam stop. The cross section and angular distribution for one such reaction, $\nu_e \, ^{208}\text{Pb} \rightarrow ^{208}\text{Bi} \, e^-$, have been calculated, using the results of an investigation of $^{208}\text{Pb} (p,n) ^{208}\text{Bi}$ at low momentum transfer. The implications of this reaction on an experiment to study neutrino oscillation are discussed.

I. INTRODUCTION

Inverse beta-decay reactions may be induced by electron neutrinos on various materials in a detector. As $\nu_e$ are produced along with $\bar{\nu}_\mu$ from $\mu^+$ decay in a beam stop, these reactions, of the form $\nu_e \, X \rightarrow e^- \, Y$, can compete with the reaction $\bar{\nu}_e \, p \rightarrow e^+ \, n$. The latter reaction is being used in a search for the oscillation $\bar{\nu}_\mu + \bar{\nu}_e$ in an experiment in preparation at LAMFF.1 Background reactions in which $Y$ is left sufficiently excited to decay by neutron emission are especially important to this experiment because the positron and neutron from $\bar{\nu}_e \, p \rightarrow e^+ \, n$ are detected in delayed

*Work performed under the auspices of US DOE.

**Visiting scientist from Hope College, Holland, Michigan.
coincidence to discriminate against cosmic-ray events. This experiment involves an 11-ton cylindrical lead shield inside the cosmic-ray veto counters, so the reactions $\nu_e^{206,207,208}_{\text{Pb}} + e^- \rightarrow 206,207,208_{\text{Bi}}$ are of particular interest.

To estimate the rate from such reactions, one must have values for the Fermi and Gamov-Teller matrix elements for the reactions in question. Published ft values from normal beta decay are inadequate because they include only F and GT strength from low-lying nuclear levels, often seriously underestimating the strength available from other nuclear states accessible at the neutrino energies involved—up to 53 MeV. Useful matrix elements for inverse beta decay can be extracted from (p,n) reaction cross sections at 0 degrees, as pointed out by Goodman, et al.\(^2\) This is possible because, like beta decay, the (p,n) reaction at small forward angles is a charge exchange reaction involving low momentum transfer.

The Gamov-Teller matrix element for a nucleus may be estimated by counting the unpaired neutrons. For $^{208}_{\text{Pb}}$, $|GT|^2 = 3(N-Z) = 142$. The cross section for $^{208}_{\text{Pb}} (p,n) ^{208}_{\text{Bi}}$ has been measured by Horen, Goodman, and coworkers,\(^3\) who found that about 1/2 of the estimated Gamov-Teller strength is contained in or near a single strong resonance at 15.6 MeV above the ground state in $^{208}_{\text{Bi}}$, well above the 7.1 MeV neutron separation energy for this nucleus. Furthermore, the entire Fermi strength, estimated as $|F|^2 = (N-Z)$, is thought to be contained in the isobaric analog state at 15.1 MeV in $^{208}_{\text{Bi}}$.

II. ESTIMATE OF CROSS SECTION

With values for the matrix elements in hand, the cross section for $\nu_e^{208}_{\text{Pb}} + e^- \rightarrow 208_{\text{Bi}}$ can be calculated, using the known $\nu_e$ spectrum from $\mu^+$ decay at rest, and including the effects of kinematics and weak magnetism. O'Connell\(^4\) has obtained the following cross section for $\nu_e n + e^- p$:

\[
\frac{d\sigma_{\nu n}}{d\Omega_{\nu e}} = \frac{6^2 kE}{4\pi^2} \left\{ 2 \left( 1 - \frac{u^2}{q^2} \right) \cos^2 \frac{\theta}{2} \right. \\
\left. + 4 \left[ F^2_A + \left( \frac{qU}{2M_p} \right)^2 \right] \left( \frac{1}{2} \frac{1}{2} \frac{\sin^2 \theta}{2} \right) - 8 F_A \left( \frac{qU}{2M_p} \right) \sin \frac{\theta}{2} \right\}
\]  

(1)
where \( G = 10^{-5}/H^2 \), \( F_A = -1.24 \)
\( M_p \) = proton mass
\( k_\nu \) = electron momentum
\( E_e \) = electron energy
\( q = \nabla - \hat{k} \), the momentum transfer
\( \nu = \text{neutrino momentum} 
\cos \theta = \hat{k} \cdot \hat{\nu}
\h = c = 1

and \( \mu_v = \mu_p - \mu_n = 4.71 \), the nuclear vector magnetic moment.

The Q value for \( \nu_e + ^{208}\text{Pb} \rightarrow ^{208}\text{Bi} \) is \(-2.9\) MeV, giving \( \omega = 18.5\) MeV for production of \(^{208}\text{Bi} \) in the 15.6 MeV Gamov-Teller state, and \( \omega = 18\) MeV for production in the isobaric analog state. The value 18.5 was used for this estimate. The results of Horen, et al. were interpreted to mean that all 44 unpaired neutrons participate in Fermi transitions for this reaction, and one half of the unpaired neutrons participate in Gamov-Teller transitions. Therefore, the cross section for \( \nu_e + ^{208}\text{Pb} \rightarrow ^{208}\text{Bi} \) was estimated by multiplying the \( F_A^2 \) and \( F_A \) terms in Eq. (1) by 1/2, evaluating \( d\sigma/d\Omega \), and multiplying the result by 44. The angular distribution appears in Fig. 1. This was integrated over solid angle to obtain the cross section as a function \( \nu \) energy. The term containing weak magnetism and kinematic effects was linear with energy to within 1% to \( E_\nu = 53\) MeV. The cross section may therefore be expressed as

\[
\sigma(E_\nu) = 7.4 \times 10^{-43} \left( E_\nu - 18.5 \right)^2 \left( 2.29 + 0.041 \ E_\nu \right) \text{cm}^2/\text{MeV}
\]

for \( E_\nu \) above the 18.5 MeV threshold.

The energy spectrum for electron neutrinos from stopped \( \mu^+ \) decay is given by

\[
\frac{dN}{dE_\nu} = \frac{12E_\nu^2(E_\nu - 53)}{(53)^4}
\]
Multiplying this by \( \sigma(E_v) \) and integrating yields the total cross section for \( \nu_e \) 208\(^{\text{Pb}} \rightarrow e^- 208\text{Bi} \) from stopped muons,

\[
\sigma = 8.3 \times 10^{-40} \text{ cm}^2.
\]

This is 57 times the cross section calculated by Donelly\(^5\) for \( \nu_e 12\text{C} \rightarrow 13\text{Ne}^- \), \( 1.46 \times 10^{-41} \text{ cm}^2 \). The electron spectrum is shown in Fig. 2.

III. RATE IN DETECTOR

Although 208\(^{\text{Pb}} \) comprises only 52% of natural lead, it has been the experience of Goodman and coworkers\(^6\) that in heavy nuclei, the Gamov-Teller strength is always concentrated in a single, large resonance, and that the location of the resonance changes quite slowly with \( Z \) and \( N \). Therefore, it was assumed for this calculation that all Pb participated as 208\(^{\text{Pb}} \) in contributing detected events. In the various bismuth isotopes produced by this reaction, the neutron separation energies are well below the excitation of the strong Gamov-Teller resonance. Neutron emission should therefore strongly dominate the de-excitation of the residual bismuth nuclei.
Thus, this reaction would produce events in the detector with almost the same signature as $\bar{\nu}_e p + n e^+$. The production rate for the reaction in 11 tons of Pb (3 x $10^{28}$ atoms), for a $\bar{\nu}_e$ flux of 1.5 x $10^{11}$/cm$^2$ LA day, is 3.7 events/day, where the LA day includes a factor of 16 for the LAMPF duty cycle. This flux assumes 750 $\mu$A of primary proton beam. The count rate in the detector will be smaller than the production rate because of several factors. First, since both the neutron and the electron must be counted in the detector, scattering of either or both particles out of the detector reduces the count rate by a factor of 4 (25%). With a 20-MeV threshold on the electron signal, 70% of the electrons will be counted. A Monte Carlo calculation indicates that, due to energy loss in the Pb, only 23% of the primary electrons will deposit greater than 20 MeV in the detector. Finally, the combined detection efficiency for neutrons and electrons is 46%. The product of these factors reduces the count rate to 0.06 counts/day, about 3/2 times our anticipated background rate. However, the maximum electron energy from the reaction is about 35 MeV. Raising the threshold on the signal reaction ($\bar{\nu}_e p + n e^+$) to 35 MeV reduces the signal rate by only 15%, so the $\bar{\nu}_e$ Pb reaction should not seriously hamper the measurement of $\bar{\nu}_e$.

On the other hand, the rate of $\nu_e$ Pb could be enhanced by adding thin lead sheet to the active volume of the detector. Instead, thin sheets would not be subject to the same factors of 25% and 25% from geometry and loss of $e^-$ energy as in the thick cylindrical shell. Thus, $\nu_e$ $^{208}$Pb could be used at least to monitor neutrino production and possibly to study $\nu_e$ disappearance, should the detector be relocated at a different distance from the beam stop.

ACKNOWLEDGEMENTS

The authors wish to express their appreciation to C.J. Stephenson and T.J. Goldman for helpful discussion of theoretical aspects of this problem, to C.A. Goulding for providing the $^{208}$Pb (p,$n$) $^{208}$Bi cross section data, and to J.M. Mack for performing the Monte Carlo calculation.
REFERENCES


