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Deuteron Disintegration, Neutral Currents, and Antineutrino Spectra from Fission

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Differential and integral cross sections for the disintegration of the deuteron by antineutrinos, both in the charge-exchange and the hypothetical charge-retention mode, are presented, together with the salient features of assumptions and calculations. The incident spectra used, those due to equilibrium and instantaneous fission, are also presented. For comparison, integral cross sections weighted by the lithium-8 spectrum are added. When weighted by the equilibrium fission spectrum, the values derived here of the integral cross sections in the two modes are $\sigma_{nn}=0.272\times10^{-44}$ cm^2 and $\sigma_{pn}=0.655\times10^{-44}$ cm^2, respectively.

INTRODUCTION

In view of detector improvements over the past 15 or so years, in sensitivity (size and efficiency) as well as in discrimination ability, the capability exists now to do quantitative low-energy neutrino and antineutrino experiments.[1,2] It is the purpose of the tables and curves presented below to permit detailed comparison of experiments involving the disintegration of the deuteron by electron antineutrinos with pertinent theory.

The detection of the charge-exchange (c.e.) disintegration,

$$\bar{\nu}_e + \mathrm{D} \rightarrow n + n + e^+, \tag{1}$$

has recently been reported.[2] The total cross section quoted for an equilibrium reactor antineutrino spectrum is in satisfactory agreement with theory.[3,4] The charge-retention (c.r.) disintegration,

$$\bar{\nu}_e + \mathrm{D} \rightarrow p + n + \bar{\nu}_e, \tag{2}$$

has also been looked for,[5] however, with insufficient sensitivity, as indicated by plausible but nevertheless speculative theories.[4,6-8] It is a good test process for the existence of weakly interacting neutral currents.

A probability of the second process comparable to that of the first can so far not be considered ruled out. A species of experiment performed, which *likely* bears *directly* on this question, is the elastic c.r. scattering of high-energy *muon* neutrinos by protons. The two most recent specimen resulted in comparatively large upper limits on the cross section: In terms of the cross section of elastic c.e. scattering of muon neutrinos by neutrons, the two upper limits are 0.5 and 0.12 $\pm$ 0.06, respectively.[9] This is in marked contrast to the widely and strongly believed but now generally abandoned previous value of 0.03, which was an impediment to $V-A$-type neutral-current theories.[10] Even the simplest charge-independent theory of the weak interaction of nucleons and leptons, see Eq. (3) below, which yields the cross section value 0.25, is easily accommodated by the larger of the two experimental upper limits; the smaller experimental upper limit, if accepted without qualification, excludes this theory, but it does accommodate members of a somewhat more sophisticated class of charge-independent theories, which also involves isoscalar currents. One member of this class, the "$v-s$ theory" (vector minus scalar in isospace), distinguished by its high symmetry, gives a cross section value of about 0.15.[11,12]

At low energies, the cross section of our c.r. process, Eq. (2), is practically unaffected by the presence of isoscalar currents.

THEORY

As nucleon-lepton interaction Hamiltonian H valid for first-order processes at low energy, we take the expression[4]

$$H = 2^{-3/2} G_V \bar{\Psi}^N \vec{\tau} \Omega_\lambda^N \Psi^N \cdot \bar{\Psi}^L \vec{\tau} \Omega_\lambda^L \Psi^L , \tag{3a}$$

where the superscripts N and L refer to nucleon (p, n) and lepton (ν, l), respectively, and where $\Omega_\lambda^L = \gamma_\lambda(1+\gamma_5)$ and $\Omega_\lambda^N = \Psi_\lambda(1+|G_A/G_V|\gamma_5)$; with $\nu = \nu_e$ goes $l = e^-$, and with $\nu = \nu_\mu$ goes $l = \mu^-$. The Ψ are, of course, local field operators, and the $\vec{\tau}$ isospin matrices. Only the c.e. part of this Hamiltonian,

$$H_{\text{c.e.}} = 2^{-1/2} G_V \bar{\Psi}^p \Omega_\lambda^N \Psi^n \bar{\Psi}^l \Omega_\lambda^L \Psi^\nu + \text{H.c.} , \tag{3b}$$

is thus far substantiated by experiment. The c.r. part,

$$H_{\text{c.r.}} = 2^{-3/2} G_V (\bar{\Psi}^p \Omega_\lambda^N \Psi^p - \bar{\Psi}^n \Omega_\lambda^N \Psi^n)(\bar{\Psi}^\nu \Omega_\lambda^L \Psi^\nu - \bar{\Psi}^l \Omega_\lambda^L \Psi^l) , \tag{3c}$$

forms a plausible theory on which to base calculations of cross sections of processes such as the low-energy antineutrino disintegration of the deuteron in the neutral mode, Eq. (2). The appearance of the same coupling-constant ratio G_A/G_V in the c.e. and c.r. parts of the interaction follows from the assumption that the nucleon current forms an isotriplet.

For the sake of precision be it mentioned that the coupling constants G_V appearing in Eqs. (3b) and (3c), respectively, may not strictly be the same; according to the Cabibbo theory[13] we have the coupling-constant relation $G_V = G\cos\theta$, where G is the coupling constant in muon decay, and $\theta \simeq 0.235$ the "Cabibbo angle" as deduced from experiment.[14] The nonzero value of the angle θ allows the occurrence of strangeness-changing c.e. processes, involving the coupling constant $G_V^{\Delta S} = G\sin\theta$. Quite analogously, we may have the relations $G_V' = G\cos\varphi$ and $G_V'^{\Delta S} = G\sin\varphi$ for c.r. processes, where the nonzero value of the "Oakes angle" φ permits strangeness-changing c.r. processes.[12,15,16] On the basis of a conceivable relationship to the CP nonconservation in K_L decay, one obtains $|\varphi| \approx 10^{-3}$, a very rough estimate. The above-described coupling-constant considerations permit one to relate the strangeness conserving c.r. and c.e. coupling constants:

$$G_V' = G_V \cos\varphi / \cos\theta . \tag{4}$$

The ratio G_A/G_V remains unaffected.

The "$\vec{\tau}\cdot\vec{\tau}$" Hamiltonian given by Eq. (3a) may be augmented by a term of "1×1 form," in other words, a scalar-scalar interaction in isospace; but (1), in the allowed approximation, in which we include the disregarding of weak magnetism effects, and (2), neglecting D-state admixtures in initial and final states, such an additional interaction does not contribute to the deuteron disintegration. Were one to go on to higher approximations, one could, in the scalar-scalar interaction, not obviously use the values for G_A/G_V and other form factors that occur in the vector-vector interaction. Rather, one might proceed analogously to Cabibbo and consider the hadron c.r. current to be a member of an $SU(3)$ octet.[11,12] Because of the vector-vector and over-all isoscalar nature of our Hamiltonian, Eq. (3a), only one set of coupling constants G_V and G_A appears there. It should be kept in mind that the numerical results below which bear on the c.r. process, Eq. (2), need only be multiplied by a ratio of coupling constants squared to reflect a simple departure from charge independence; see, e.g., Eq. (4).

The cross sections for monoenergetic antineutrinos of the reactions given here as Eqs. (1) and (2), differential in "reduced nucleon energy" E_r, are calculated to be

$$\frac{d\sigma}{dE_r} = 2\pi \left(\frac{G_A^{\text{eff}}}{\sqrt{2}} \right)^2 |ME|^2 \rho . \tag{5}$$

G_A^{eff} equals G_A and $G_A/2$ for the c.e. and c.r. mode, respectively.

$$|ME|^2 = \frac{32\pi B^{1/2}(B^{1/2}+E_s{}^{1/2})^2}{M^{3/2}(E_r+E_s)(E_r+B)^2} \tag{6a}$$

for the c.e. mode and twice this expression for the c.r. mode.

$$\rho = (M^{3/2}/8\pi^4)(Q - B_1 - E_r)[(Q - B_1 - E_r)^2 - m^2]^{1/2} E_r{}^{1/2} , \tag{7}$$

where $m = m_e$ in the c.e. and $m = 0$ in the c.r. mode. Q is the incident antineutrino energy, B the binding energy of the deuteron, B_1 the latter plus the neutron-proton mass difference, E_s the "virtual singlet energy level" of the two-nucleon system, and M the mass of the nucleon. E_r is the energy of the two outgoing nucleons in their own c.m. system. The inconsequential energy associated with the c.m. motion of the nucleons has been neglected.

In the derivation of Eq. (6a) the nuclear force was assumed to have a zero effective range. This excellent approximation permits integration of the differential cross section for the c.r. mode, resulting in a *simple* closed-form expression for the total cross section ($B' = B - E_s$),

$$\sigma^{\circ}=\frac{2}{\pi^2}G_A{}^2\frac{B^{1/2}(B^{1/2}+E_s{}^{1/2})^2}{B'^2}\left\{B'(E+2B')(E-B)^{1/2}+2E\left[E\left(1-\frac{B'}{2B}\right)-2B'\right]B^{1/2}\arctan\frac{(E-B)^{1/2}}{B^{1/2}}\right.$$
$$\left.-\,2(E-B')^2E_s{}^{1/2}\arctan\frac{(E-B)^{1/2}}{E_s{}^{1/2}}\right\}. \tag{8}$$

For a nonzero effective range the right side of Eq. (6a) is replaced by[17]

$$\frac{32\pi}{M^{3/2}}\frac{B^{1/2}}{1-(MB)^{1/2}r_t}\;\frac{[B^{1/2}+E_s{}^{1/2}-\frac{1}{4}M^{1/2}(r_s+r_t)B+\frac{1}{4}M^{1/2}(r_s-r_t)E]^2}{E+(\frac{1}{2}M^{1/2}r_sE+E_s{}^{1/2})^2}. \tag{6b}$$

The constants, other than well-known masses, used in the computations are[18]:

$G_A=-1.403\times10^{-11}\ \mathrm{MeV}^{-2}$, $B=2.225$ MeV, $B_1=3.519$ MeV, $E_s=7.38\times10^{-2}$ MeV,

$r_s=1.22\times10^{-2}\ \mathrm{MeV}^{-1}$, $r_t=8.67\times10^{-3}\ \mathrm{MeV}^{-1}$.

In the neutral mode the expression for $|ME|^2$ is twice the one in the c.e. mode because, in the former, the incoming antineutrino is absorbed by neutron and proton, whereas in the latter it is absorbed only by the proton. This factor is, of course, overcompensated by the differing vertex strengths.

In considering the c.e. mode, one may be interested in the cross-section differential in the positron energy E_e. This is immediately obtained from the cross section $d\sigma/dE_r$, Eq. (5), as applied to the c.e. mode, by replacing E_r everywhere by $Q-E_e-B_1$.

RESULTS

The following results of computations based on Eqs. (5) through (7) of the c.e. and c.r. processes, given here as Eqs. (1) and (2), are presented in this note: (1) The differential cross sections $d\sigma_{nn}/dE_r$ and $d\sigma_{pn}/dE_r$ versus reduced nucleon energy E_r for incident equilibrium fission antineutrinos. For the c.e. process, there is also a plot of $d\sigma_{nn}/dE_e$ versus positron energy E_e. See Fig. 1. The subscripts nn and pn refer to the respective outgoing nucleons. Neglecting the neutron-proton mass difference, when it appears, the reduced nucleon energy is given by

$$E_r=(\vec{p}_1-\vec{p}_2)^2/4M, \tag{9a}$$

with $\vec{p}_1$ and $\vec{p}_2$ the nucleon momenta, and M the nucleon mass. For detectable nucleon energies the relation

$$E_r=2E_N \tag{9b}$$

is usually well satisfied, see below; the subscript N stands for nucleon. (2) The cross sections integrated from the detection thresholds of the reduced nucleon energy E_r^d and the positron energy E_e^d. These cross sections are denoted by σ^d and σ'^d, respectively. They are given in percent of the respective integral cross sections σ_{pn} and σ_{nn}. See Table I. Calculations have been made regarding the conditions under which one is allowed to identify "reduced nucleon spectra" with actual exodent nucleon spectra, without committing an error

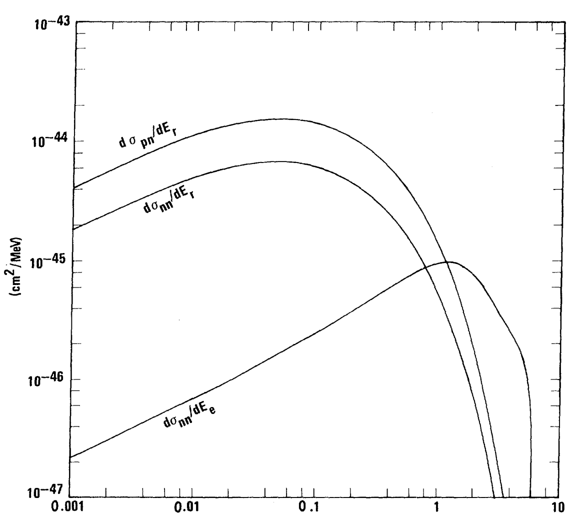

FIG. 1. Differential cross sections of the reactions $\bar{\nu}_e+D\rightarrow n+n+e^+$ and $\bar{\nu}_e+D\rightarrow p+n+\bar{\nu}_e$ for incident antineutrinos from equilibrium fission. E_r = reduced nucleon energy $\simeq 2E_p$ or $2E_n$.

TABLE I. Cross sections for $\bar{\nu}_e+D\rightarrow n+n+e^+$ and $\bar{\nu}_e+D\rightarrow p+n+\bar{\nu}_e$, integrated from the detection thresholds E_r^d and E_e^d. $E_r\simeq 2E_n$ or $2E_p$.

Incident $\bar{\nu}$ spectrum	E_r^d (keV)	$100\times\frac{\sigma^d_{nn}}{\sigma_{pn}}$	$100\times\frac{\sigma^d_{pn}}{\sigma_{pn}}$	E_e^d (keV)	$100\times\frac{\sigma'^d_{nn}}{\sigma_{nn}}$
Equilibrium	0	100 [a]	100 [b]	0	100 [a]
fission	50	89.3	89.8	100	99.4
	100	77.7	78.6	250	97.5
	250	51.8	53.4	500	92.2
	500	28.3	29.9	1000	76.3

[a] $\sigma_{nn}=0.272\times10^{-44}\ \mathrm{cm}^2$.
[b] $\sigma_{pn}=0.655\times10^{-44}\ \mathrm{cm}^2$.

of greater than x percent. Thus, with $x \simeq 10$ and incident antineutrinos of 5.5 (8.5) [13.5] MeV the spectra agree for $E_N > 50$ (200) [500] keV.[7] The relation between nucleon energy E_N and E_r is then given by Eq. (9a). (3) The integral cross sections weighted by time-dependent spectra of incident fission antineutrinos. Here we use the spectra of antineutrinos emitted between 0 and t sec after fission. Normalization is to one particle per cm^2 between $t=0$ and $t\rightarrow\infty$. See Table II. Between 0 and t sec, when $t<\infty$, the cross sections appearing in Table II are not cross sections in the strict sense of the word, since the number of incident antineutrinos is then less than one per cm^2. The cross sections are expressed in percent of the cross sections valid for one incident antineutrino per cm^2 conforming to the equilibrium fission spectrum. In Table II the number of antineutrinos emitted per fission between 0 and t sec after fission is also exhibited, in percent of the total number emitted per fission. (4) The fission spectra used in terms (1) through (3) are plotted in Fig. 2. The time-dependent spectra are fits to the histograms of Brewer, King, and Mears, which are based on those nuclides having a cumulative fission yield of more than 1/100 of 1%, 260 in all.[19] The equilibrium spectrum is the one of Avignone, Blakenship, and Darden.[20] As $t\rightarrow\infty$, the Brewer spectrum clearly contains fewer high-energy antineutrinos than the Avignone spectrum, while the total number of antineutrinos (and β particles) emitted per fission is in both cases approximately 6.1. As a result one has $(\sigma_{pn}^A-\sigma_{pn}^B)/(\sigma_{pn}^A+\sigma_{pn}^B)=0.177$ and $(\sigma_{nn}^A-\sigma_{nn}^B)/(\sigma_{nn}^A+\sigma_{nn}^B)=0.206$, the superscripts A and B standing for Avignone and Brewer, respectively. Since the Avignone spectrum is based on more recent decay information, we have used it whenever the equilibrium fission spectrum was called for. But the work of Brewer *et al.* appears to be the most complete to date as far as time-dependent spectra go.

The cross-section computations leading to the results given here are all based on the nonzero effective range, Eq. (6b); use of the zero effective range leads to an agreement with them of better than 2%.

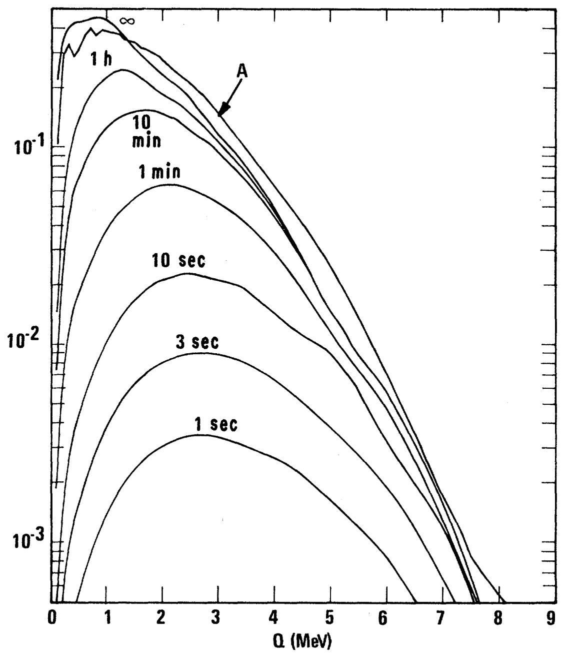

FIG. 2. Antineutrino spectra between 0 and t seconds after fission based on Ref. 19, and equilibrium spectrum (A) from Ref. 20, normalized to one antineutrino per fission.

Computations with the Li^8 spectrum were also done to show the possible advantage of using Li^8 for an antineutrino source, perhaps by working near a lithium-cooled reactor. The integral cross sections are here $\sigma_{nn}=47.6\times10^{-44}$ cm^2 and $\sigma_{pn}=40.8\times10^{-44}$ cm^2.[21]

This material represents the theoretical end product of a work on neutral currents begun by R. W. King and one of the authors, who is deeply grateful to Professor King for his invaluable help.[22]

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TABLE II. Integral cross sections for $\bar{\nu}_e+D\rightarrow n+n+e^+$ and $\bar{\nu}_e+D\rightarrow p+n+\bar{\nu}_e$ between 0 and t seconds after fission. $N(t)$ = No. of antineutrinos emitted between 0 and t seconds after fission.

Incident $\bar{\nu}$ spectrum	$100\times\frac{\sigma_{nn}(t)}{\sigma_{nn}}$	$100\times\frac{\sigma_{pn}(t)}{\sigma_{pn}}$	$100\times\frac{N(t)}{N(\infty)}$
Between 0 and $t=3$(sec)	37.5	26.2	3.43
after fission $=10$	63.4	48.1	8.01
$=100$	84.3	74.2	20.5
$=600$	99.5	95.3	44.1
$=\infty$	100 [a]	100 [b]	100 [c]

[a] $\sigma_{nn}=0.179\times10^{-44}$ cm^2. [b] $\sigma_{pn}=0.458\times10^{-44}$ cm^2. [c] $N(\infty)=6.13$.

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