Charged and neutral current neutrino reactions in deuterium at reactor energies

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Calculations for the reactor averaged cross section $\langle\sigma(\bar{\nu}_e{}^2\mathrm{H}\to nne^+)\rangle$ are given for four different reactor neutrino spectra in common use. Use is made of existing neutral current data for $\langle\sigma(\bar{\nu}_e{}^2\mathrm{H}\to np\bar{\nu}_e)\rangle$ to obtain the elementary particle model form factors. Results for $\langle\sigma(\bar{\nu}_e{}^2\mathrm{H}\to nne^+)\rangle$ vary from 2.08×10^{-45} cm^2 to 1.35×10^{-45} cm^2 with errors strongly dependent on spectrum accuracy.

[NUCLEAR REACTIONS Disintegration cross sections at reactor energies for $^2\mathrm{H}(\bar{\nu}_e,e^+)nn$ calculated for several spectra using the elementary particle model.]

Recent experimental results[1] for the cross sections $\langle\sigma(\bar{\nu}_e{}^2\mathrm{H}\to e^+nn)\rangle$ and $\langle\sigma(\bar{\nu}_e{}^2\mathrm{H}\to\bar{\nu}_e np)\rangle$ have led to a renewed interest in these reactions as a possible test for neutrino oscillations and a resultant number of theoretical calculations for these processes. The results for the cross sections are, of course, spectrum dependent. This is particularly true for the charged current process, which has a threshold of approximately 4 MeV as opposed to 2.2 MeV for the neutral current process. Hence, it is more sensitive to the higher energy region[2] of the reactor neutrino spectrum which is in general difficult to calculate.

In this paper we make use of the existing[1] neutral current neutrino reaction data to obtain values for the charged current reaction cross section. We perform these calculations for four spectrums presently in use.[3–5] These calculations are done via the elementary particle model[6] making use of a previous result of the author.[7,8] This procedure has the advantage of being relatively model independent. In addition, the neutral current results should be independent of neutrino oscillation phenomena and are in acceptable agreement with theory.

We write the matrix element for the neutral and charged current matrix elements to the lowest order in G as

$$M(\nu+{}^2\mathrm{H}\to p+n+\nu)=\frac{1}{\sqrt{2}}G\langle pn\,|J_\lambda^N(0)\,|{}^2\mathrm{H}\rangle\bar{v}_\nu\gamma^\lambda(1-\gamma_5)v_\nu \quad (1)$$

and

$$M(\bar{\nu}_e+{}^2\mathrm{H}\to n+n+e^+)=\frac{1}{\sqrt{2}}G\cos\theta_C\langle nn\,|J_\lambda^\dagger(0)\,|{}^2\mathrm{H}\rangle\bar{v}\gamma^\lambda(1-\gamma_5)v\ , \quad (2)$$

respectively, where $G(=1.02\times10^{-5}m_p{}^2)$ is the weak coupling constant, θ_C is the Cabbibo angle, and

$$\begin{aligned}J_\lambda^N&=J_\lambda^{(3)}(0)-\sin^2\theta_w J_\lambda^{(\mathrm{em})}(0)\ ,\\ J_\lambda^{(3)}(0)&=V_\lambda^{(3)}(0)-A_\lambda^{(3)}(0)\ ,\\ J_\lambda&=V_\lambda(0)-A_\lambda(0)\ ,\end{aligned} \quad (3)$$

is the weak hadronic current. In the processes we are considering here at reactor energy, the matrix element of the vector current is negligible.[9] We therefore concentrate our attention on the axial current matrix element, which we write[10–12] as

$$\langle np\,|A_\lambda^{(3)}(0)\,|{}^2\mathrm{H}\rangle=\eta\bar{u}(p_1)(F_A^{(3)}\xi_\lambda+F_P^{(3)}\xi\cdot Qq_\lambda/M_d{}^2)\gamma_5 v(p_2)\ , \quad (4)$$

$$\langle nn\,|A_\lambda^+(0)\,|{}^2\mathrm{H}\rangle=\eta\bar{u}(p_1)\left[F_A\xi_\lambda+F_P\frac{\xi\cdot Qq_\lambda}{M_d{}^2}\right]\gamma_5 v(p_2)\ ,$$

where $p_{1\mu}$ and $p_{2\mu}$ are the four-momenta of the two nucleons, ξ_μ is the deuteron polarization vector, $Q_\mu=p_{1\mu}+p_{2\mu}$, d_μ is the deuteron four-momentum, $q_\mu=Q_\mu-d_\mu$, and M_d is the deuteron mass. All energies here have units of MeV; all mo-

menta have units MeV/c, and all parameters used here have units consistent with these choices. The form factors describing the axial current have been obtained in an earlier work.[7,8] In the energy range which we are considering they are given by

$$|F_A|^2=|\mathcal{F}_A|^2 f_A{}^2 , \tag{5}$$

$$|\mathcal{F}_A|^2=\frac{(3.61\times10^1+6.13\times10^{-1}q_0)}{[(q_0-\alpha)^2+\beta^2]} , \tag{6a}$$

$$f_A(q^2)=(1.0-q^2/M_A{}^2)^{-2}M_A=912 \text{ MeV} ,$$

$$F_A^{(3)}=\pm F_A/\sqrt{2} . \tag{6b}$$

These form factors were obtained from pion photoproduction data and yield reasonable results for muon capture and for neutrino reactions in deuterium at LAMPF energies.[7,8] There is no reason, however, to expect these form factors to accurately extrapolate to threshold neutrino processes. What we do here, therefore, is use the available neutral current neutrino results to modify the existing form factors in such a way that they reproduce this data and also do not change significantly the previous results for muon capture, neutrino reactions at LAMPF energies, pion capture, and pion photoproduction. This requirement fixes the choice for the form factors.

Because the measurement for the neutral current cross section is averaged over the reactor spectrum it is necessary to unfold the spectrum in order to obtain the elementary particle model[13] form factors. The results obviously depend upon the spectrum chosen. We therefore use four spectra in current use, namely those by Avignone and Greenwood[3] (AG), Davis *et al.*[4] (DVMS), Borovoi[5] *et al.* (BDK), and an experimental spectrum[14] deduced from the reaction $\bar{\nu}_e+p\rightarrow n+e^+$. We then use the form factors so obtained along with the corresponding spectrum to calculate $\langle\sigma(\bar{\nu}_e d\rightarrow nne^+)\rangle$. What we are doing therefore, is checking whether the Reines, Sobel, and Pasierb (RSP) results for $\langle\sigma(\bar{\nu}_e d\rightarrow nne^+)\rangle$ are consistent with their results for $\langle\sigma(\bar{\nu}_e d\rightarrow np\bar{\nu}_e)\rangle$ and any of the spectra currently in use. We note that because the observed value for $\langle\sigma(\bar{\nu}_e d\rightarrow nne^+)\rangle$ is somewhat below the theoretical value used by RSP for the same cross section, this tends to increase our values for R slightly relative to their calculations. This is because our $(\sigma_{ncd})_{\text{exp}}/(\sigma_{ncd})_{\text{th}}$ is always unity, but a smaller neutral current cross section will in this model lead to smaller form factors and, hence, a smaller $(\sigma_{ccd})_{\text{th}}$. As a check we also used the AG spectrum combined with their value[3] for $\langle\sigma(\bar{\nu}_e d\rightarrow nne^+)\rangle$ as a check on this procedure.

We find that when we attempt to satisfy the criteria mentioned above, we can do so by varying the parameters α and β of Eq. (6), an appropriate approximation of the fit used in the earlier work mentioned. The original fitting of these was relatively insensitive to the data used to obtain them, but the threshold processes are very sensitive to them. We obtain our α and β by requiring that $\langle\sigma(\bar{\nu}_e d\rightarrow np\bar{\nu}_e)\rangle$ be fit in such a way that any induced variation in the pion photoproduction cross sections of the original fit be minimized. In all cases variations are less than 5% in all data, including the neutrino cross sections and muon capture rates obtained in our earlier paper. From the matrix elements[7,8] $|M(\nu^2H\rightarrow nne^+)|^2$ and $|M(\nu^2H\rightarrow np\bar{\nu})|^2$ obtained in our earlier work, setting F_V, the vector form factor to zero, we obtain values for the appropriate cross sections.

In Table I we list the values obtained for α, β, and $\langle\sigma(\bar{\nu}_e{}^2\text{H}\rightarrow nne^+)\rangle$, and in Fig. 1 we plot the cross sections for $\bar{\nu}_e+{}^2\text{H}\rightarrow n+n+e^+$ for the above mentioned values of α and β for neutrino energy from threshold to 10 MeV. The errors in the procedure used here come primarily from errors expected in form factors induced by an error of roughly 20% in the measured $\langle\sigma(\bar{\nu}_e{}^2\text{H}\rightarrow np\bar{\nu}_e)\rangle$ data. In addition, a rough estimate of the electromagnetic part of the final state interaction yields a potential error of up to 10%, yielding a total in the 25–30 % range.

Using the R value defined by Reines *et al.*,[1] $R=[(\sigma_{ccd})_{\text{exp}}/(\sigma_{ccd})_{\text{th}}]/[(\sigma_{ncd})_{\text{exp}}/(\sigma_{ncd})_{\text{th}}]$ and recalling that because $(\sigma_{ncd})_{\text{exp}}$ was used to fit $(\sigma_{ncd})_{\text{th}}$, $(\sigma_{ncd})_{\text{exp}}/(\sigma_{ncd})_{\text{th}}=1$ in our case, we obtain the values for R given in the second column of Table II. Finally, to examine the oscillation hypothesis we assume the experimentally determined spectrum is indeed an oscillated one and in turn as-

TABLE I. Spectrum averaged cross sections corresponding to the four spectra in general use are tabulated along with the corresponding values of α and β.

Spectra	α	β	$\langle\sigma(\bar{\nu}_e{}^2\text{H}\rightarrow nne^+)\rangle\times10^{-45}$ cm^2
AG	3.72	2.76	1.81
BDK	3.52	2.95	1.76
DVMS	3.75	2.47	1.51
Experimental	3.77	2.25	1.35

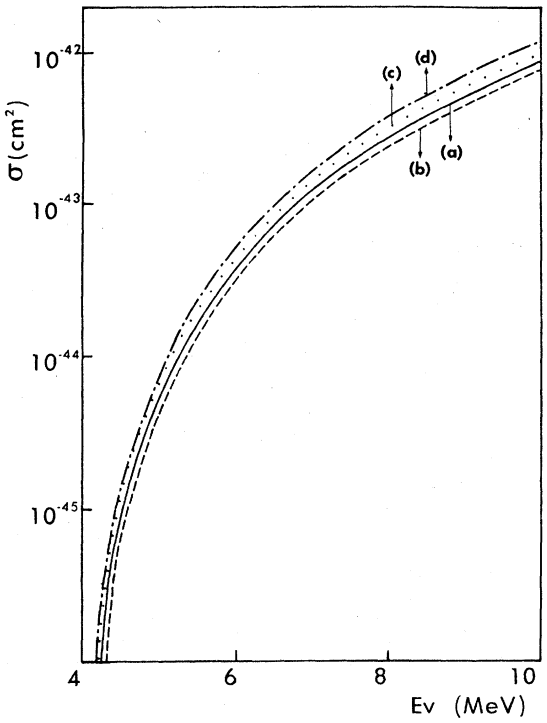

FIG. 1. Plot of cross sections for the reaction $\bar{\nu}_e + {}^2\mathrm{H} \rightarrow n + n + e^+$. Curves (a), (b), (c), and (d) correspond to values of α and β obtained for the AG, BDK, DVMS, and "experimental" spectra.

sume that the AG, DVMS, and BDK spectra are the true unoscillated spectra, respectively. We then use the values we obtained earlier for α and β appropriate to each of those spectra to calculate $\langle \sigma(\bar{\nu}_e d \rightarrow nne^+) \rangle$, but we average this cross section over the experimental spectrum. The R values so obtained are listed in Table II column 3.

As can be seen from column 3 of Table II, the

TABLE II. Table of R values obtained for the various spectra in use, under the assumption of oscillation and nonoscillation. Because in the case of oscillation the experimental spectrum is assumed to be oscillated, there is no entry for R experimental.

Spectra	R (no oscillation)	R (oscillation)
AG	0.45 ± 0.20	0.87 ± 0.37
BDK	0.47 ± 0.21	0.82 ± 0.35
DVMS	0.54 ± 0.24	0.74 ± 0.32
Experimental	0.61 ± 0.26	

AG, BDK, and DVMS spectrum yield R values consistent with unity and are therefore consistent with each of these being on unoscillated spectrum and the experimental spectrum being an oscillated one. On the other hand, the largest R value, which includes the error in $(\sigma_{ccd})_{\mathrm{exp}}$ and R obtained for the experimental spectrum with no assumption of oscillation are roughly consistent with unity.

We note that we have not considered spectra uncertainty. However, there is an estimate[1] of about 25% uncertainty in the higher energy part of the DVMS spectra. If this represents an overestimate, the DVMS and experimental spectra begin to overlap, and the possibility for consistency between these two spectra and no oscillation exists. Our conclusion, therefore, is that the presently available data is not sufficient to distinguish among the possibilities with certainty.

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