

DISINTEGRATION OF THE DEUTERON BY REACTOR ANTINEUTRINOS

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The recently measured neutral-current cross section of $(3.8 \pm 0.9) \times 10^{-45} \text{ cm}^2$ by Pasierb et al for $\bar{\nu}_e + D \rightarrow \bar{\nu}_e + p + n$ is consistent with the Weinberg–Salam model only if the spectrum for reactor antineutrinos has a high energy tail which is significantly lower than the theoretical spectrum

Recently, the weak neutral current cross section $\sigma_{\nu D}$ for the reaction $\bar{\nu}_e + D \rightarrow \bar{\nu}_e + p + n$ with reactor antineutrinos has been measured to be $(3.8 \pm 0.9) \times 10^{-45} \text{ cm}^2$ by Pasierb et al [1]. This measurement is of particular interest because it is the only measurement of a reaction induced by the isovector, axial-vector, weak neutral current [2,3]. This current is independent of the single free parameter in the Weinberg–Salam (WS) model [4] but is related to the well known charged, axial currents by a rotation in the isospin space. Therefore (in the WS model) $\sigma_{\nu D}$ is uniquely determined by known properties of the deuteron [3,5–7].

Here we point out that there is a significant (greater than three standard deviations) difference between the measured value for $\sigma_{\nu D}$ and the value of $(7 \pm 0.4) \times 10^{-45} \text{ cm}^2$ predicted [3,6,7] in the WS model, when the theoretical spectrum for $\bar{\nu}_e$ is used in the calculation. However, the discrepancy would be removed if an “empirical” $\bar{\nu}_e$ spectrum consistent with a recent measurement by Reines et al [8] were used.

For an antineutrino of energy E_ν , the cross section for $\bar{\nu}_e + D \rightarrow \bar{\nu}_e + p + n$ is given by

$$\sigma_{\nu D}(E_\nu) = 1.14\beta^2 \times 10^{-43} \times \int_0^{E_\nu - B} \frac{E_r^{1/2}(E_\nu - B - E_r)}{B^{1/2}(E_s + E_r)(B + E_r)^2} dE_r \quad (\text{cm}^2)$$

$$= 1.14\beta^2 \times 10^{-43} \times \left\{ \frac{E_\nu}{B - E_s} \left[\frac{(B + E_s)E_\nu}{(B - E_s)B} - 4 \right] \tan^{-1} \left(\frac{E_\nu - B}{B} \right)^{1/2} - 2 \left(\frac{E_s}{B} \right)^{1/2} \left(\frac{E_\nu}{B - E_s} - 1 \right)^2 \tan^{-1} \left(\frac{E_\nu - B}{E_s} \right)^{1/2} + \left(\frac{E_\nu - B}{B} \right)^{1/2} \left(2 + \frac{E_\nu}{B - E_s} \right) \right\} (\text{cm}^2), \quad (1)$$

where $B = 2.22 \text{ MeV}$ is the binding energy of the deuteron, $E_s = (\hbar c)^2 / (a_s^2 M) = 0.0738 \text{ MeV}$, $a_s = -23.7 \text{ fm}$ being the singlet scattering length of the np system, E_r is the relative kinetic energy of the np system. The cross section $\sigma_{\nu D}$ is obtained by folding $\sigma_{\nu D}(E_\nu)$ over the reaction $\bar{\nu}_e$ -spectrum $n(E_\nu)$,

$$\sigma_{\nu D} = \int_B^\infty \sigma_{\nu D}(E_\nu) n(E_\nu) dE_\nu / \int_0^\infty n(E_\nu) dE_\nu \quad (2)$$

The parameter β in eq (1) is the amplitude for the axial vector, isovector neutral current, as defined by Hung and Sakurai [9]. In the WS model, $\beta = 1$. The value for β determined [10] by high-energy ν -hadron scattering experiments is $\beta = 0.95 \pm 0.12$. The “standard” value of $\beta = 1$ will be used in the following analysis.

In ref [3], the $\bar{\nu}_e$ -spectrum of Avignone [11] was parametrized as

$$\begin{aligned}
n(E_\nu) &= 0, & E_\nu < 0.055 \text{ (MeV)}, \\
&= a \exp(-bE_\nu), & 0.055 \leq E_\nu \leq 3.4 \\
&= c \exp(-dE_\nu), & 3.4 < E_\nu,
\end{aligned} \quad (3)$$

with (in units of MeV^{-1}) $a = 3.63$, $b = 0.543$, $c = 17.8$, $d = 1.01$. A value $\sigma_{\nu D} = 7.1 \times 10^{-45} \text{ cm}^2$ was obtained. This result is consistent with those attained by Ahrens and Lang [6], $\sigma_{\nu D} = 6.6 \times 10^{-45} \text{ cm}^2$ and by Avignone and Greenwood [7], $\sigma_{\nu D} = 7.4 \times 10^{-45} \text{ cm}^2$, who used slightly different versions of the $\bar{\nu}_e$ -spectrum [11,7]. These results are more than three standard deviations greater than the measured value [1] of $(3.8 \pm 0.9) \times 10^{-45} \text{ cm}^2$.

A plausible explanation of this discrepancy is that the $\bar{\nu}_e$ -spectrum that affects the experiment of ref [1] may be different from that derived indirectly from empirical fission yields, mass defects and β -decay schemes [7,11]. There is in fact some experimental support for this interpretation. In search for neutrino oscillation, Reines et al [8] observed that the measured number of $\bar{\nu}_e$ in the range $E_\nu > 4.5 \text{ MeV}$ is significantly less than that expected from the $\bar{\nu}_e$ -spectrum of Avignone [11]. The $\bar{\nu}_e$ -spectrum of (3) can be reconciled with this observation by allowing the spectrum to have a faster exponential drop-off in the higher energy region. Reductions of 25% and 35%, respectively, in the number of $\bar{\nu}_e$ at $E = 5.3 \text{ MeV}$, representing the upper and lower limits of the measured number [8], yield the two sets of parameters for $n(E_\nu)$ designated no. 2 and no. 3 in table 1. No. 1 is the parametrization obtained in ref [3]. These parametrized spectra together with Avignone's theoretical spectrum [11] and the data of Reines et al [8] are shown in fig. 1. The curve labeled "a" gives an arbitrarily normalized

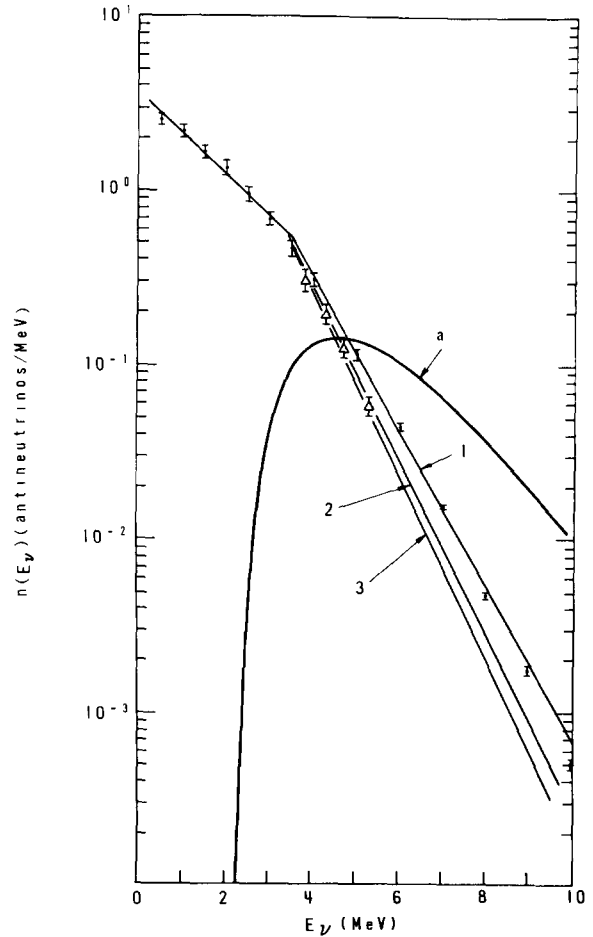


Fig. 1 The segmented exponentials labeled 1, 2 and 3 are simple representations of the $\bar{\nu}_e$ -spectrum corresponding to the parameter sets 1, 2 and 3, respectively, given in table 1. The points (●) are (some of) those deduced from fission data by Avignone [11]. The four points (Δ) are those measured by Reines et al [8], normalized relative to Avignone's spectrum. Curve "a" is an arbitrarily normalized $\sigma_{\nu D}(E_\nu)n(E_\nu)$ computed from spectrum 1.

Table 1
Parameters for $\bar{\nu}_e$ -spectrum and results for $\sigma_{\nu D}$

Parameter set	a (MeV^{-1})	b (MeV^{-1})	c (MeV^{-1})	d (MeV^{-1})	$\sigma_{\nu D}$ (10^{-45} cm^2)	N_ν
no. 1 a)	3.63	0.543	17.8	1.01	7.1 b)	6.00 c)
no. 2	3.63	0.543	29.6	1.16	5.1	5.93
no. 3	3.63	0.543	38.5	1.24	4.4	5.89

a) From ref [3]

b) Ahren and Lang [6] obtained 6.6 and Avignone and Greenwood [7] obtained 7.4, respectively, using two slightly different $\bar{\nu}_e$ -spectra, see refs [3] and [7] for details

c) $N_\nu = \int_0^\infty n(E_\nu) dE_\nu$

$\sigma_{\nu D}(E_\nu) n(E_\nu)$ calculated from $n(E_\nu)$ no 1. This curve clearly demonstrates the sensitivity of $\sigma_{\nu D}$ to the $\bar{\nu}_e$ -spectrum in the region $3 \lesssim E_\nu \lesssim 9$ MeV.

The computed $\sigma_{\nu D}$ are given in column 6 of table 1. The cross sections computed with the reduced spectra, $\sigma_{\nu D} = 5.1 \times 10^{-45} \text{ cm}^2$ for no 2 and $\sigma_{\nu D} = 4.4 \times 10^{-45} \text{ cm}^2$ for no 3, are now in agreement with the measured $\sigma_{\nu D}$.

The cause of the reduced $\bar{\nu}_e$ -spectrum remains an unresolved problem. Reines et al [8] believe the reduction is incompatible with neutrino oscillation. It is worthwhile noticing that the altered $\bar{\nu}_e$ -spectrum yields very little change in the number of antineutrino per fission, $N_\nu = \int_0^\infty n(E_\nu) dE_\nu$, as shown in column 7 of table 1. If one rejects the possibility of a reduced spectrum, then from eq (1) and taking $\sigma_{\nu D}^{\text{theory}} = (7.0 \pm 0.4)\beta^2 \times 10^{-45} \text{ cm}^2$, one obtains $|\beta| = 0.73 \pm 0.10$, a result which is barely consistent with the value obtained from [8] high energy ν -hadron scattering data, it is a very small value compared to the standard $\beta = 1$ of the WS model.

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