Isospin dependence of nucleon-nucleon interactions and its effect on the cross section $\sigma(\bar{\nu}_e + d \to n + n + e^+)$

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The cross section for the reaction $\bar{\nu}_e + d \to n + n + e^+$ was calculated for ten values of the n-n scattering length from -15.0 to -23.7 fm and for three very different fission antineutrino spectra. The maximum effect is to change the conclusion of Reines, Sobel, and Pasierb from $R < 0.63$ to $R < 0.71$ where $R \equiv \Gamma_{\rm exp}/\Gamma_{\rm theor}$ and $\Gamma = \langle\sigma(\bar{\nu}_e + d \to n + n + e^+)\rangle / \langle\sigma(\bar{\nu}_e + d \to n + p + \bar{\nu}_e)\rangle$.

Recently Reines, Sobel, and Pasierb[1] reported an anomalous value for the ratio R defined as

$$R \equiv \Gamma_{\rm exp}/\Gamma_t ,$$

where Γ_t is the theoretically calculated quantity

$$\Gamma_t \equiv \langle\sigma(\bar{\nu}_e + d \to n + n + e^+)\rangle / \langle\sigma(\bar{\nu}_e + d \to n + p + \bar{\nu}_e)\rangle$$

$$\equiv \bar{\sigma}_{\rm cc}/\bar{\sigma}_{\rm nc} ,$$

and where the symbols $\langle\sigma\rangle$ and $\bar{\sigma}$ imply integration over nucleon energy and an average over the reactor antineutrino spectrum. The experimental value reported in Ref. 1 was $\Gamma_{\rm exp} = 0.167 \pm 0.093$ while theoretical values $\Gamma_t^{\rm AG} = 0.44$ and $\Gamma_t^{\rm DVMS} = 0.42$ were calculated using the antineutrino spectra of Avignone and Greenwood[2] (AG) and Davis *et al.*[3] (DVMS), respectively. The reported values were $R = 0.38 \pm 0.21$ and 0.40 ± 0.22 using $\Gamma_t^{\rm AG}$ and $\Gamma_t^{\rm DVMS}$, respectively. This ratio should be unity and its anomalously small value has been attributed to possible neutrino oscillations. Many theoretical treatments of the weak breakup of the deuteron are cited in a recent article by Ahrens and Gallaher.[4] It has been pointed out, however, that earlier calculations do not account for the isospin dependence of the nucleon-nucleon interaction[5,6] and the resulting difference in the n-n and n-p singlet scattering lengths which appear explicitly in effective-range theory. Following the arguments given earlier,[7] one can specialize a general result given by Ali and Dominguez[8] to obtain the following simple expression for $\bar{\sigma}$:

$$\bar{\sigma} = \frac{4G^2}{\pi^2}\int d\omega \int dE_k \frac{m^{3/2}\gamma(\gamma a_s - 1)^2 E_k^{1/2}(\omega - E_d - \delta - E_k)[(\omega - E_d - \delta - E_k)^2 - m_l^2]^{1/2}P(\omega)}{(mE_k a_s^2 + 1)(\gamma^2 + mE_k)^2} , \tag{1}$$

where (m = reduced nucleon-rest mass energy), $\gamma = (mE_d)^{1/2} = 45.71$ MeV, a_s is the singlet scattering length, E_d is the deuteron binding energy, E_k is the nucleon energy, δ is the proton-neutron rest-mass energy difference, m_l is the lepton rest-mass energy, and $P(\omega)$ is the normalized antineutrino spectrum. The neutral-current cross section[2,7] is obtained by simply dividing by 2 and setting $m_l = \delta = 0$. The values for Γ_t given in this paper were obtained by fine grained numerical integration over nucleon energy E_k and antineutrino energy ω, respectively.

The n-p singlet scattering length $a_s(np)$ has been measured many times and has the well-known value[9] -23.715 ± 0.015 fm. The n-n singlet scattering length $a_s(nn)$ is not nearly as well known hence an accurate analysis of the data of Reines *et al.*[1] must be made for the entire possible range of $a_s(nn)$ and not just for a single value. Also the effect of the antineutrino spectrum shape on this isospin-breaking effect should be clearly understood.

The earlier (1975) world average given in Ref. 5 for $a_s(nn)$ was -16.6 ± 0.6 fm. Two values of $a_s(nn)$ have been reported recently which have been derived from data from the reaction $\pi^- + d \to n + n + \gamma$. In 1977 Alder *et al.*[10] reported a value of $-18.1 < a_s(nn) < -17.8$ fm and Baer[11] reported a value $a_s(nn) = 18.4 \pm 0.4$ fm. In 1979 Gabioud *et al.*[12] reported a value $a_s(nn) = 18.5 \pm 0.5$ fm which is the final version of the results of Alder *et al.*[10] While one is tempted to select these later values to evaluate the effect on the calculated values of Γ_t, we have chosen instead to evaluate Γ_t for 10 values of $a_s(nn)$ from -15.0 to -23.715 fm. These integrals appear in Table I for both the AG spectrum and for the DVMS spectrum. It is clear that the dependence of the quantity $\Delta\Gamma_t/\Gamma_t'$ is extremely insensitive to the differences in the shapes of these neutrino spectra as is R. In addition we

TABLE I. Average cross section $\bar{\sigma}_{cc}$ for the reaction $\nu e + d \to n + n + e^+$ averaged over AG spectra of Ref. 2, the DVMS spectrum of Ref. 3, and the experimental spectrum from the UCI inverse-β-decay data. All cross sections are given in units of 10^{-45} cm^2.

$a_s(nn)$ (fm)	$\bar{\sigma}_{cc}$	Γ_t [a]	$\Delta\Gamma_t/\Gamma_t'$ [b]	$\bar{\sigma}_{cc}$	Γ_t	$\Delta\Gamma_t/\Gamma_t'$	$\bar{\sigma}_{cc}$	$\Delta\bar{\sigma}_{cc}/\bar{\sigma}_{cc}'$ [c]
	Calculated with AG spectrum			Calculated with DVMS spectrum			Calculated with UCI spectrum	
−15.0	2.47	0.380	13.2%	1.69	0.357	13.0%	1.21	14.8%
−16.0	2.52	0.388	11.1%	1.73	0.366	11.0%	1.24	12.7%
−17.0	2.58	0.397	9.2%	1.76	0.372	9.7%	1.27	10.6%
−18.0	2.62	0.403	7.6%	1.80	0.380	7.8%	1.30	8.5%
−18.4	2.64	0.406	6.9%	1.81	0.382	7.3%	1.31	7.8%
−19.0	2.67	0.411	6.0%	1.83	0.387	6.1%	1.32	7.0%
−20.0	2.71	0.417	4.4%	1.86	0.393	4.6%	1.34	5.6%
−21.0	2.75	0.423	3.2%	1.88	0.397	3.6%	1.37	3.5%
−22.0	2.78	0.428	1.9%	1.91	0.404	1.9%	1.39	2.1%
−23.715	2.84	0.436	0.0	1.96	0.415	0.0	1.42	0.0%

[a] $\bar{\sigma}_{nc} = 6.55 \times 10^{-45}$ cm^2 given in Ref. 2.

[b] Γ_t' is evaluated using $a_s(nn) = -23.715$ fm.

[c] Γ_t' cannot be calculated from experimental spectra because the experimental data are not reliable below about 4 MeV. $\bar{\sigma}_{cc}'$ was calculated with $a_s(nn) = -23.715$ fm.

have calculated the average charged-current cross section, for the above range of $a_s(nn)$, using a spectrum derived from the University of California, Irvine (UCI) inverse-β-decay experiment at 11.2 m from the reactor core.[13] It is not possible to calculate the neutral-current cross section using such experimental spectra because they become unreliable below about 4 MeV. The same information can be gained from observing the quantity $\Delta\bar{\sigma}_{cc}/\bar{\sigma}_{cc}'$ defined as $[\bar{\sigma}_{cc}(-23.715\text{ fm}) - \bar{\sigma}_{cc}(a_s(nn))]/\bar{\sigma}_{cc}(-23.715\text{ fm})$. This quantity shows exactly the same dependence on the singlet scattering length as the quantity $\Delta\Gamma_t/\Gamma_t'$. It is evident from examining Table I that the dependence on neutrino spectrum shape is small but observable and must be considered.

Finally it is instructive to list the limiting values of R allowed by the data of Ref. 1 using the minimum values of several of the reported ranges of $a_s(nn)$ and to compare them with that reported in Ref. 1 which we call $R(-23.715)$. We find

$$0.17 < R(-23.715) < 0.60\,, \tag{2a}$$

$$0.18 < R(-18.4) < 0.64\,, \tag{2b}$$

and

$$0.19 < R(-16.0) < 0.67\,, \tag{2c}$$

when evaluated with the AG spectrum while we find

$$0.18 < R(-23.715) < 0.63\,, \tag{3a}$$

$$0.19 < R(-18.4) < 0.68\,, \tag{3b}$$

and

$$0.20 < R(-16.0) < 0.71\,, \tag{3c}$$

when the DVMS spectrum is used. We can see that although the isospin dependence of the nucleon-nucleon interaction can lead to a non-neglegible effect on the interpretation of the disintegration of the deuteron by antineutrinos, it cannot explain the surprising result reported in Ref. 1. The present calculations will also be valuable for the interpretation of the data from future experimental investigations of these reactions regardless of how our beliefs concerning fission antineutrino spectra and neutron-neutron scattering lengths evolve.

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