PHYSICAL REVIEW D VOLUME 23, NUMBER 1 1 JANUARY 1981

Isospin breaking and final-state interactions in the weak breakup of the deuteron

W. R. Gibbs and G. J. Stephenson, Jr.
Theoretical Division, Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87545
(Received 11 July 1980)

We find that the difference in n-n and n-p $^1S_0$ scattering lengths leads to corrections to the ratio of neutral- to charged-current breakup of the deuteron of as much as ten percent.

Recent measurements by Reines, Sobel, and Pasierb[1] have been interpreted as evidence for neutrino instability. These measurements were of the ratio of charged-current to neutral-current breakup of the deuteron. More specifically,

$$R=\frac{\bar{\nu}_e+d\to n+n+e^+}{\bar{\nu}_e+d\to n+p+\bar{\nu}_e}.$$

This ratio is compared to theoretical ratios calculated by assuming no neutrino oscillations. They find $R_{\rm exp}/R_{\rm theo}=0.38\pm0.21$ or 0.40 ± 0.22, depending on the assumed neutrino spectrum. We address ourselves to a question in the calculation of the theoretical ratio of rates.

Since the final nucleons are at very low energies the integration of the cross sections over the neutrino spectrum must take into account the strong interaction of the two nucleons in the $T=1$, $^1S_0$ final state. This calculation has been done by three groups.[2] In these treatments a finite-range deuteron has been used (which is very little different from the case of zero range) and the phase shift has been taken from the effective-range expansion as is normal for these types of calculation. Thus the $T=1$, $^1S_0$ scattering length enters into the calculation in a (potentially) strong way since the final-state enhancement at very low relative nucleon-nucleon energy is proportional to the square of this quantity. This number is very well known for n-p scattering (-23.7 fm) and this value has been used for the calculation of the theoretical ratio.

If isospin were absolutely conserved, there would be no more to the story. However, the p-p and n-n values of the scattering length are also well measured and known to be different from the n-p value. World average values[3] for the n-n case lie in the range -16.6 ± 0.6 fm. However, a recent measurement[4] of high quality obtains -18.5 ± 0.5 fm.

If all of the contribution to the rate comes from *very* low N-N energies, a correction to $R_{\rm theo}$ of order $\frac{1}{2}$ would be present and explain the result of Ref. 1 without any instability on the part of the neutrino. This conclusion is mitigated, however, since the main effect of the final-state interaction is to *shift* the strength of the spectrum rather than to increase it. Thus an increase at very low energies is partly compensated by a decrease at higher energies (see Fig. 1).

To estimate the actual size of this effect, we have approximated the neutrino spectrum[5] by a simple exponential. With this approximation, the expression for the total cross section is

$$\sigma=\int_0^\infty dE_{nn}E_{nn}^{1/2}J^2(E_{nn},a)$$
$$\times\int_{E_{\rm th}}^\infty dE_2(E_2-E_{\rm th}+m)$$
$$\times[(E-E_{\rm th}+m)^2-m^2]^{1/2}\phi(E_2),$$

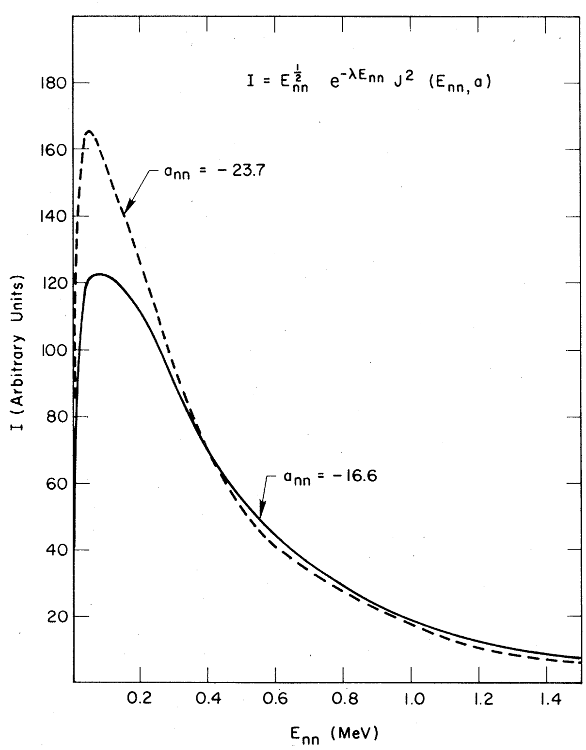

FIG. 1. Plot of the integrand of the relevant factor for $\lambda=1.0$ MeV^{-1}. Shown are plots for $a_{nn}=-23.7$ fm and $a_{nn}=-16.6$ fm. Notice that the large effect at small relative nucleon-nucleon energies is compensated by a smaller effect over a larger range at higher energies.

where J^2 is the overlap of the deuteron and appropriate $^1S_0$ scattering state,

$$J(E,a) = [k^2 + (-1/a + 1.4k^2)^2]^{-1/2}\,\frac{0.232 - 1/a + 1.4k^2}{(0.0538 + k^2)} - \frac{1.39 - 1/a + 1.4k^2}{(1.932 + k^2)} - 0.3374\,,$$

$\phi(E_2)$ is the neutrino spectrum, $E_{\text{th}} = E_0 + E_{nn}$, $m = m_e$, and $E_0 = 4.0$ MeV for the charged-current reaction, and $m = 0$ and $E_0 = 2.226$ MeV for the neutral-current reaction. With the approximate neutrino spectrum, the expression factorizes as follows:

$$\sigma = \int_0^\infty dE_{nn} E_{nn}^{\;1/2} J^2(E_{nn}, a) e^{-\lambda E_0 - \lambda E_{nn}} \times \int_0^\infty d\epsilon\,(\epsilon + m)[(\epsilon + m)^2 - m^2]^{1/2} e^{-\lambda\epsilon}$$

$$= \left\{\int_0^\infty dE_{nn} E_{nn}^{\;1/2} e^{-\lambda E_{nn}} J^2(E_{nn}, a)\right\} e^{-\lambda E_0} \times \left\{\int_0^\infty d\epsilon\, e^{-\lambda\epsilon}(\epsilon + m)[(\epsilon + m)^2 - m^2]^{1/2}\right\}.$$

Hence we are concerned with the ratio of the first factor for a value of a appropriate to the n-n channel compared to the n-p channel. In Table I we present the ratio of the value of the integral for the n-n channel (appropriate to charged-current reactions) to that for the n-p channel (appropriate to neutral-current reactions), for λ equal to 1.0 and 1.5 MeV^{-1} and for the two mentioned values of a_{nn}. To correct the value of Reines *et al.* for this effect, the theoretical ratio must be multiplied by the appropriate number from Table I.

TABLE I. Ratio of final-state interaction factors for the charged-current to neutral-current reactions, $a_{np} = -23.7$ fm.

a_{nn} (fm) \ λ (MeV^{-1})	1.0	1.5
−16.6	0.924	0.903
−18.5	0.948	0.934

The two exponentials used here bracket the various calculated spectra and hence give reasonable limits on the size of the effect. The absolute normalization of the neutrino spectrum (which is the main difference between Avignone and Greenwood and Davis *et al.*[5]) drops out of the ratio. A full calculation requires a two-dimensional integral and is beyond the scope of this comment.

We note that this change by itself is not large enough to alter the conclusions of Ref. 1 but should be included in any analysis to determine the mixing angle, mass difference, and confidence level.

After this work was submitted, our attention was called to the work of Barger, Whisnant, Cline, and Phillips[6] in which this effect is considered. We thank Dr. Barger for sending us a proof copy of that paper. This work was supported by the U. S. Department of Energy.

[1]F. Reines, H. W. Sobel, and E. Pasierb, Phys. Rev. Lett. 45, 1307 (1980).
[2]S. A. Fayans, L. A. Mikaelyan, and Yu. L. Dobrynin, J. Phys. G 5, 209 (1979); Tino Ahrens and T. P. Lang, Phys. Rev. C 3, 979 (1971); Tino Ahrens and Lawrence Gallaher, Phys. Rev. D 20, 2714 (1979).
[3]B. Kühn, Fiz. Elem. Chastits At. Yadra 6, 347 (1975) [Sov. J. Part. Nucl. 6, 139 (1976)].
[4]J. C. Alder *et al.*, Helv. Phys. Acta 51, 90 (1978); B. Gabioud *et al.*, Phys. Rev. Lett. 42, 1508 (1979).
[5]For representative calculated spectra, see B. R. Davis, P. Vogel, F. M. Mann, and R. E. Schenter, Phys. Rev. C 19, 2259 (1979); F. T. Avignone III and Z. D. Greenwood, Phys. Rev. D 17, 154 (1978); A. A. Borovoi, Yu. L. Dobrynin, and V. I. Kopeikin, Yad. Fiz. 25, 264 (1977) [Sov. J. Nucl. Phys. 25, 144 (1922)].
[6]V. Barger, K. Whisnant, D. Cline, and R. J. N. Phillips, J. Phys. G 6, L165 (1980).