Constraints on Two-Body Axial Currents from Reactor Antineutrino-Deuteron Breakup Reactions

Malcolm Butler

Department of Astronomy and Physics, Saint Mary's University, Halifax, NS B3H 3C3 Canada
mbutler@ap.stmarys.ca

Jiunn-Wei Chen

Department of Physics, University of Maryland, College Park, MD 20742, USA
jwchen@physics.umd.edu

Petr Vogel

Department of Physics, California Institute of Technology, Pasadena, California 91125, USA
vogel@citnp10.caltech.edu

Abstract

We discuss how to reduce theoretical uncertainties in the neutrino-deuteron breakup cross-sections crucial to the Sudbury Neutrino Observatory's efforts to measure the solar neutrino flux. In effective field theory, the dominant uncertainties in all neutrino-deuteron reactions can be expressed through a single, common, isovector axial two-body current parameterized by $L_{1,A}$. After briefly reviewing the status of fixing $L_{1,A}$ experimentally, we present a constraint on $L_{1,A}$ imposed by existing reactor antineutrino-deuteron breakup data. This constraint alone leads to an uncertainty of 6-7% at 7 MeV neutrino energy in the cross-sections relevant to the Sudbury Neutrino Observatory. However, more significantly for the Sudbury experiment, the constraint implies an uncertainty of only 0.7% in the ratio of charged to neutral current cross-sections used to verify the existence of neutrino oscillations, at the same energy. This is the only direct experimental constraint from the two-body system, to date, of the uncertainty in these cross-sections.
I. INTRODUCTION

Recent results from the Sudbury Neutrino Observatory (SNO) [1] highlight the importance of a precise determination of neutrino-deuteron breakup reaction cross-sections. The three reactions used by SNO to detect the $^8B$ solar flux are

\[ \nu_e + d \rightarrow p + p + e^- \quad \text{(CC)}, \]
\[ \nu_x + d \rightarrow p + n + \nu_x \quad \text{(NC)}, \]
\[ \nu_x + e^- \rightarrow \nu_x + e^- \quad \text{(ES)}. \]

The charged current reaction (CC) is sensitive exclusively to electron-type neutrinos, while the neutral current reaction (NC) is equally sensitive to all active neutrino flavors ($x = e, \mu, \tau$). The elastic scattering reaction (ES) is sensitive to all active flavors as well, but with reduced sensitivity to $\nu_\mu$ and $\nu_\tau$. Detection of these three reactions allows SNO to determine the electron and non-electron active neutrino components of the solar flux, and it is then obvious that the cross sections for these three reactions are important inputs to SNO. However, while the ES cross section is very well determined, the CC and NC cross sections have never been tested to high precision.

Theoretically, the complications in the CC and NC processes are due to two-body currents which are irreducible interactions involving leptonic external currents and two nucleons. The two-body currents can be calculated either through meson exchange diagrams aided by modeling of any unknown weak couplings, or can be parameterized using effective field theory (EFT). In both cases, experimental data from some other process are required in order to calibrate the unknowns in the problem. In EFT, this calibration procedure can be described in an economic and systematic way. The reason is that, up to next-to-next-to-leading order (NNLO) in EFT, all low-energy weak interaction deuteron breakup processes depend on a common isovector axial two-body current, parameterized by $L_{1,A}$ [2]. This implies that a measurement of any one of the breakup processes could be used to fix $L_{1,A}$.

In this paper, we will briefly review the EFT approach and discuss experiments that could be used to fix $L_{1,A}$. Then we present the constraint on $L_{1,A}$ using reactor $\bar{\nu}d$ scattering.

II. EFFECTIVE FIELD THEORY

For the deuteron breakup processes used to detect solar neutrinos, where $E_\nu < 15$ MeV, the typical momentum scales in the problem are much smaller than the pion mass $m_\pi (\sim 140$ MeV). In these systems pions do not need to be treated as dynamical particles since they only propagate over distances $\sim 1/m_\pi$, much shorter than the scale set by the typical momentum of the problem. Thus the pionless nuclear effective field theory, EFT($\hat{\pi}^0$) [3, 4, 5, 6, 7, 8], is applicable.

In EFT($\hat{\pi}^0$), the dynamical degrees of freedom are nucleons and non-hadronic external currents. Massive hadronic excitations such as pions and the delta resonance are “integrated out,” resulting in contact interactions between nucleons. Nucleon-nucleon interactions are calculated perturbatively with the small expansion parameter

\[ Q \equiv \frac{(1/a, \gamma_1, p)}{\Lambda} \quad (1) \]

which is the ratio of the light to heavy scales. The light scales include the inverse S-wave nucleon-nucleon scattering length $1/a (\lesssim 12$ MeV) in the $^1S_0$ channel, the deuteron binding
momentum \( \gamma (= 45.7 \text{ MeV}) \) in the \( ^3S_1 \) channel, and the typical nucleon momentum \( p \) in the center-of-mass frame. The heavy scale \( \Lambda \) is set by the pion mass \( m_\pi \). This formalism has been successfully applied to many processes involving the deuteron \([8, 9]\), including Compton scattering \([10, 11]\), \( np \rightarrow d\gamma \) for big-bang nucleosynthesis \([12, 13]\), \( vd \) scattering for SNO physics \([2]\), the solar \( pp \) fusion process \([14, 15]\), and parity violating observables \([16]\). Also studies on three-nucleon systems \([17]\) have revealed highly non-trivial renormalizations associated with three body forces in the \( s_{1/2} \) channel (e.g., \( ^3\text{He} \) and the triton). For other channels, precision calculations were carried out to higher orders \([7, 18]\).

In Ref. \([2]\), EFT(\( \pi / \)) is applied to compute the cross-sections for four channels (CC, NC, \( \nu_e + d \rightarrow e^- + n + n \) (\( \nu \text{CC} \)) and \( \nu_x + d \rightarrow \nu_x + n + p \) (\( \nu \text{NC} \)) to next-to-next-to-leading order (NNLO), up to 20 MeV (anti)neutrino energies. As already mentioned, these processes have been shown to depend on only one parameter, \( L_{1,A} \), an isovector axial two-body current. This dependence is subject to an intrinsic uncertainty in our EFT calculation at NNLO of less than 3%. Through varying \( L_{1,A} \), the potential model results of Refs. \([19, 20]\) are reproduced to high accuracy for all four channels. This confirms that the \( \sim 5\% \) difference between Refs. \([19, 20]\) is due largely to different assumptions made about short distance physics.

The same two-body current \( L_{1,A} \) also contributes to the proton-proton fusion process \( p + p \rightarrow d + e^+ + \nu_e \). This is the primary reaction in the \( pp \) chain of nuclear reactions that power the sun, reactions which in turn generate the neutrino flux to be observed by SNO. The calculations in EFT(\( \pi / \)) were carried out first to second order \([14]\), and then to fifth order \([15]\).

### III. FIXING \( L_{1,A} \)

In order to determine neutrino-deuteron breakup reaction cross-sections and the \( pp \) fusion amplitude to high precision, one needs a precise determination of \( L_{1,A} \). Naive dimensional analysis gives \( |L_{1,A}| \sim 6 \text{ fm}^3 \) when the renormalization scale \( \mu \) is set to \( m_\pi \). This implies that the contribution from \( L_{1,A} \) is at the 7–8\% level at a neutrino energy of 7 MeV. However, this is a \( \mu \)-dependent statement and cannot be used to draw comparisons between two-body contributions in the EFT calculation and conventional potential model calculations. It is therefore important to consider how one can constrain \( L_{1,A} \) experimentally. This is a daunting task, as most weak processes where \( L_{1,A} \) contributes are difficult (if not practically impossible) to measure accurately in the laboratory. Further, some experiments such as the measurement of the flux-averaged CC cross-section using neutrinos from stopped muon decays \([21]\), employ neutrino energies greater than 20 MeV. At this time, the convergence of the calculations of Ref. \([2]\) is uncertain at these higher energies, so we are forced to ignore such experiments. Here we list some observables that could be used to determine \( L_{1,A} \):

1. \( \nu_e + d \rightarrow e^- + p + p \): the planned ORLaND detector \([22]\) has proposed to measure this CC process with \( \sim 1\% \) accuracy. This measurement, combined with higher order calculations in EFT, would calibrate SNO’s CC and NC processes to the same level of accuracy.

2. \( \nu \) \( \tau \) \( e \) \( d \) breakup reactions: the main topic of this letter. We discuss the extraction of \( L_{1,A} \) in next section.
3. solar $\nu_x e$ elastic scattering (ES): the three channels available for measuring the solar neutrino flux, ES, CC, and NC are all measured by SNO, and ES is measured at Super-K to high precision. In general, these results can be used to constrain three quantities: the electron and non-electron active neutrino components of the solar flux, and $L_{1,A}$. As statistics improve in all three channels, SNO could become self-calibrating in that it could use this determination of $L_{1,A}$ to fix the CC and NC cross-sections [23].

4. muonic atom capture $\mu^- + d \rightarrow \nu_\mu + n + n$ [24, 25]: this reaction can involve significant energy and momentum transfers. EFT(\#) may fail in regions of phase space where the neutrons are energetic, but should be rapidly convergent in the region of phase space where the two neutrons move slowly [25]. Coincident measurements of those slow neutrons to the required precision are very difficult. However, indirect high-precision measurements of the total capture rate are feasible at PSI by comparing the lifetime of $\mu^-$ to that of $\mu^+$ in a deuterium target (thereby avoiding the need to detect final-state neutrons), then subtracting the (easier to measure) faster neutron events [26].

5. Tritium beta decay $^3H \rightarrow ^3He + e^+ + \nu_e$: under the assumption that three-body currents are negligible, Schiavilla et al. [27] used this process to fix the two-body current and made a prediction for the solar fusion process $p + p \rightarrow d + e^+ + \nu_e$, with an accuracy of better than 1%. This prediction by Schiavilla et al. [27] can be translated to a constraint on $L_{1,A}$ using the EFT formula of [13]. After updating the pion-nucleon coupling $g_A$ from 1.26 to 1.267, we obtain $L_{1,A}^{\text{Schiavilla et al.}} = 6.5 \pm 2.4 \text{ fm}^3$ at NNLO. This result includes the theoretical uncertainty discussed in Ref. [15]. If we truncate the results from Ref. [13] at NNLO, the expression for $\Lambda(0)$ becomes

$$\Lambda_{\text{NNLO}}(0) = 2.61 + 0.0104 \left( \frac{L_{1,A}}{1 \text{ fm}^3} \right) + O(1.5\%)$$

(2)

If we compare this to Schiavilla et al., we find $L_{1,A}^{\text{Schiavilla et al.}} = 4.2 \pm 3.7 \text{ fm}^3$. This latter result is more appropriate for comparison to the constraints presented later in this work. We note also that, following the approach of Schiavilla et al., other calculations have made use of tritium beta decay to make predictions for other weak processes, and all claim an accuracy of $\sim 1\%$ [28].

6. Helioseismology: the ability of the standard solar model to reproduce acoustic mode ($p$-mode) oscillations in the Sun to high precision can be used to constrain the $pp$ fusion cross-section, and thus $L_{1,A}$. Assuming that the solar model must reproduce these oscillations to the same precision, it is found that $L_{1,A} = 7.0 \pm 5.9 \text{ fm}^3$ [29] at NNNLO, or $L_{1,A} = 4.8 \pm 6.7 \text{ fm}^3$ using eq. 2 at NNLO. These numbers also include the theoretical uncertainty in the reduced matrix element for $pp$ fusion [13] (but not from other theoretical uncertainties in the solar model). It should be noted that this constraint is more an indicator of the scale and sign of $L_{1,A}$. There are other physical inputs to the solar model (e.g., opacities) that will weaken this constraint if also allowed to vary.

So far, we have only given numerical constraints on $L_{1,A}$ in methods 5 and 6. These constraints rely on certain assumptions that require deeper theoretical study. In the next section we will look at fixing $L_{1,A}$ using method 2, namely reactor $\nu_e d$ breakup reactions.
IV. A CONSTRAINT FROM REACTOR ANTINEUTRINO EXPERIMENTS

The charged current $\nu_e d \rightarrow e^+ nn$ ($\nu_{\text{CC}}$) and neutral current $\nu_x d \rightarrow \nu_x np$ ($\nu_{\text{NC}}$) deuteron disintegration have been observed in several experiments with reactor antineutrinos. We can use the results of these experiments to constrain the parameter $L_{1,A}$.

The results of the pioneering experiment at Savannah River [30, 31] have been subsequently revised [32]. The fuel composition for that experiment has not been published, and the effect of the revision on the error bars is uncertain. Thus we do not use the Savannah River experiment in our fit, but concentrate instead on the more recent measurements at Rovno [33], Krasnoyarsk [34], and Bugey [35] where sufficient information is available.

The thresholds ($E_{\text{th}}$) of the $\nu_{\text{NC}}$ and $\nu_{\text{CC}}$ reactions are 2.23 MeV, and 4.03 MeV, respectively. These relatively high thresholds, particularly for the $\nu_{\text{CC}}$ reaction, make the yield more dependent on the reactor fuel composition than for the usual $\bar{\nu}_e p \rightarrow e^- n$ reaction. If the fuel composition is known (i.e., the fraction of fissions corresponding to $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, and $^{241}\text{Pu}$), one can evaluate the $\bar{\nu}_e$ flux $N_{\nu_e}(E)$ in units of the number of $\bar{\nu}_e$ per fission, using the known $\nu_e$ flux produced by each reactor fuel [36].

The results of Refs. [33, 34] are expressed as the averaged cross section (in cm$^2$/fission)

$$\bar{\sigma}_{\text{fission}} = \int_{E_{\text{th}}}^{E_{\text{max}}} N_{\nu_e}(E)\sigma(E)\,dE,$$  \hfill (3)

where $E_{\text{max}}$ is the maximum energy available in the reactor spectrum (the flux $N_{\nu_e}(E) \rightarrow 0$ at $E_{\text{max}}$).

The results of Ref. [35] have a different normalization (in cm$^2$/$\bar{\nu}_e$):

$$\bar{\sigma}_\nu = \frac{\int_{E_{\text{th}}}^{E_{\text{max}}} N_{\nu_e}(E)\sigma(E)\,dE}{\int_{E_{\text{th}}}^{E_{\text{max}}} N_{\nu_e}(E)\,dE},$$  \hfill (4)

which can be converted to $\bar{\sigma}_{\text{fission}}$ easily (Note the erratum to that reference, however). The measured averaged cross sections $\bar{\sigma}_{\text{fission}}$ for each of Refs. [33, 34, 35] are listed in Table I in units of cm$^2$/fission.

The $\nu_{\text{CC}}$ and $\nu_{\text{NC}}$ cross sections were calculated to NNLO in EFT($\pi$) and were parameterized in the form

$$\sigma(E) = a(E) + b(E)L_{1,A},$$  \hfill (5)

with the computed $a(E)$ and $b(E)$ tabulated in Ref. [2]. It has been noted that these cross-sections must be updated to include the most recent determination of $g_A$ and to include electromagnetic radiative corrections [37]. To change the pion-nucleon coupling from $g_A = 1.26$ used in Ref. [2] to the most up-to-date value $1.267 \pm 0.004$ [38], we multiply $a(E)$ by $(1.267/1.26)^2$ and multiply $b(E)$ by $(1.267/1.26)$. The inclusion of the electromagnetic radiative corrections increase $\nu_{\text{NC}}$ by 1.5% and $\nu_{\text{CC}}$ by 3.5% [39], based on the method of Refs. [40, 41]. Performing the corresponding integrals of $a(E)N_{\nu_e}(E)$ and $b(E)N_{\nu_e}(E)$ and comparing with the experiment, we extract the parameter $L_{1,A}$ from each measurement and it is shown in the last column of Table I. The central value of $L_{1,A}$ varies dramatically between measurements. This is largely due to the fact that the term involving $L_{1,A}$ is a small contribution to the cross-section, in that a change in $L_{1,A}$ of 1 fm$^3$ would produce an $\mathcal{O}(1\%)$ change in the cross-sections. The error bars listed are derived from the experimental uncertainties; they are dominated by the statistics of each measurement which we assume (for simplicity) to be gaussian in our analysis. Even though some common systematic errors
TABLE I: Average cross-sections for charged and neutral current $\bar{\nu}_e d$ breakup ($\nu_{CC}$ and $\nu_{NC}$, respectively) and the inferred values of $L_{1,A}$ from each of the three reactor experiments at Rovno [33], Krasnoyarsk [34], and Bugey [35].

| Location          | $\sigma_{fission} (10^{-44} \text{cm}^2/\text{fission})$ | $L_{1,A} (\text{fm}^3)$ |
|-------------------|----------------------------------------------------------|--------------------------|
| Rovno CC          | 1.17 ± 0.16                                              | 17.4 ± 13.9              |
| Rovno NC          | 2.71 ± 0.47                                              | −2.0 ± 13.8              |
| Krasnoyarsk CC    | 1.05 ± 0.12                                              | −1.3 ± 9.5               |
| Krasnoyarsk NC    | 3.09 ± 0.30                                              | 1.8 ± 8.1                |
| Bugey CC          | 0.95 ± 0.20                                              | −1.5 ± 17.2              |
| Bugey NC          | 3.15 ± 0.40                                              | 11.1 ± 11.7              |

are present we shall treat each of the three $\nu_{CC}$ and $\nu_{NC}$ as an independent determination of $L_{1,A}$ to obtain $\overline{L}_{1,A} = 3.6 \pm 7.1 \text{ fm}^3$ and $3.5 \pm 6.0 \text{ fm}^3$, respectively. The grand average of all six experiments results in $\overline{L}_{1,A} = 3.6 \pm 4.6 \text{ fm}^3$. These averages were obtained by summing over the individual results ($L_{1,A})_i$ with the error bar $\delta_i$:

$$\overline{L}_{1,A} = \sum_i \frac{(L_{1,A})_i}{\delta_i^2} / \sum_i \frac{1}{\delta_i^2},$$

with the total uncertainty

$$\delta[\overline{L}_{1,A}] = \left( \sum_i \frac{1}{\delta_i^2} \right)^{-1/2}$$

Clearly, the averaging resulted in a substantial reduction of the uncertainty. For this to be reasonable, the measurements must be truly independent. The total $\chi^2$ of the averaging procedure is only $\chi^2_{\text{tot}} = 2$. This relatively (but not alarmingly) low value might suggest that there could be correlations between the $\nu_{CC}$ and $\nu_{NC}$ results of each set of experiments. Possible sources of these correlations include: the simultaneous extraction of $\nu_{CC}$ and $\nu_{NC}$ cross-sections through the measurement of two and one neutron events for $\nu_{CC}$ and, respectively, $\nu_{NC}$, and; the dependence on the calculated antineutrino spectra (though this is a small effect). It is difficult to speculate on other possible sources of correlations in the data.

In addition, there are $\lesssim 3\%$ errors in eq. (6) due to higher order corrections. This results in a systematic error of $\lesssim 3 \text{ fm}^3$ on $L_{1,A}$. Summing up these two uncertainties in quadrature, we have

$$\overline{L}_{1,A}^{\text{reactor}} = 3.6 \pm 5.5 \text{ fm}^3,$$

which is consistent with the constraints from tritium beta decay and helioseismology, yet totally independent of both.

Given the importance of this result, one may ask whether a new high precision experiment of the reactor $\bar{\nu}_e$ induced deuteron breakup could result in a substantially more precise determination of $L_{1,A}$. This seems unlikely, since an improvement in accuracy to $\pm 3 \text{ fm}^3$ (for example), equal to the above-stated systematic error, would require the measurement of the cross section $\sigma_{fission}$ to $\sim 3\%$ accuracy. Such a measurement seems rather challenging at the present time.
Finally, it should be noted that all reactor deuteron breakup data were obtained in very short baseline experiments. Thus, they are unaffected by neutrino oscillations, given current constraints [38].

V. CONCLUSIONS

We have discussed how to reduce the theoretical uncertainties in the $\nu d$ breakup cross-sections crucial for SNO’s measurements of the solar neutrino flux. In effective field theory, the dominant uncertainties can be expressed through an isovector axial two-body current $L_{1,A}$. We have discussed experiments that can fix $L_{1,A}$ and have presented a constraint on this quantity from reactor antineutrino deuteron breakup experiments. The reactor antineutrino constraint alone on $L_{1,A}$ can be translated to an uncertainty of 6-7% in the CC and NC reactions used by SNO, at a neutrino energy of 7 MeV. The most recent results from SNO verifying the existence of solar neutrino oscillations [1], however, rely only on the CC/NC ratio which is insensitive to $L_{1,A}$ [2, 3]. In fact, the reactor constraint on $L_{1,A}$ implies an uncertainty of only 0.7% in the CC/NC ratio at 7 MeV [4]. However, a 6-7% level of uncertainty in cross-sections would have a significant effect on extractions of the $^{8}$B flux. It is encouraging that existing analyses using the methods discussed in Section III produce values of $L_{1,A}$ which are consistent in both sign and magnitude but, clearly, more work must be done to constrain $L_{1,A}$ to higher precision.

Acknowledgments

We thank Hamish Robertson for useful discussions and Hank Sobel for discussions regarding the Bugey experiment. MB is supported by the Natural Sciences and Engineering Research Council (NSERC) Canada. JWC is supported in part by the U.S. Dept. of Energy under grant No. DE-FG02-93ER-40762 and PV is supported by the U.S. Dept. of Energy grant No. DE-FG03-88ER-40397.

[1] Q.R. Ahmad et al., Phys. Rev. Lett. 87, 071301 (2001); nucl-ex/0204008; nucl-ex/0204009.
[2] M.N. Butler and J.W. Chen, Nucl. Phys. A675, 575 (2000); M.N. Butler, J.W. Chen and X. Kong, Phys. Rev. C 63, 035501 (2001).
[3] D.B. Kaplan, M.J. Savage and M.B. Wise, Nucl. Phys. B478, 629 (1996).
[4] D.B. Kaplan, Nucl. Phys. B494, 471 (1997).
[5] U. van Kolck, hep-ph/9711222, Nucl. Phys. A645 273 (1999).
[6] T.D. Cohen, Phys. Rev. C55, 67 (1997); D.R. Phillips and T.D. Cohen, Phys. Lett. B390, 7 (1997); S.R. Beane, T.D. Cohen, and D.R. Phillips, Nucl. Phys. A632, 445 (1998).
[7] P.F. Bedaque and U. van Kolck, Phys. Lett. B428, 221 (1998).
[8] J.W. Chen, G. Rupak and M.J. Savage, Nucl. Phys. A653, 386 (1999).
[9] J.W. Chen, G. Rupak and M.J. Savage, Phys. Lett. B464, 1 (1999).
[10] S.R. Beane and M.J. Savage, Nucl. Phys. A694, 511 (2001).
[11] H.W. Griesshammer and G. Rupak, Phys. Lett. B529, 57 (2002).
[12] J.W. Chen and M.J. Savage, Phys. Rev. C 60, 065205 (1999).
[13] G. Rupak, Nucl. Phys. A678, 405 (2000).
[14] X. Kong and F. Ravndal, Nucl. Phys. A656, 421 (1999); Nucl. Phys. A665, 137 (2000); Phys. Lett. B470, 1 (1999); Phys. Rev. C 64, 044002 (2001).
[15] M. Butler and J.W. Chen, Phys. Lett. B520, 87 (2001).
[16] M.J. Savage, Nucl. Phys. A695, 365 (2001).
[17] P.F. Bedaque, H.W. Hammer and U. van Kolck, Phys. Rev. Lett. 82, 463 (1999); Nucl. Phys. A 676, 357 (2000); H.-W. Hammer and T. Mehen, Phys. Lett. B 516, 353 (2001).
[18] P.F. Bedaque, H.-W. Hammer and U. van Kolck, Phys. Rev. C 64, 044002 (2001).
[19] S. Ying, W.C. Haxton and E. M. Henley, Phys. Rev. C 45, 1982 (1992); Phys. Rev. D 40, 3211 (1989).
[20] S. Nakamura, T. Sato, V. Gudkov and K. Kubodera, Phys. Rev. C 63, 034617 (2001).
[21] S.E. Willis et al., Phys. Rev. Lett. 44, 522 (1980). S.E. Willis, Ph.D. Thesis (1979), LA-8030-T, UMI-80-12103-mc.
[22] F.T. Avignone and Yu.V. Efremenko, in Proceedings of the 2000 Carolina Conference on Neutrino Physics, ed. K. Kubodera (World Scientific, 2000) pp. 214-234.
[23] J.W. Chen, K.M. Heeger, and R.G.H. Robertson, in preparation.
[24] S. Ando, T.S. Park, K. Kubodera and F. Myhrer, Phys. Lett. B533, 25 (2002).
[25] J.W. Chen, in preparation.
[26] P. Kammel, private communication; P. Kammel et al., nucl-ex/0202011, Contributed to International RIKEN Conference on Muon Catalyzed Fusion and Related Exotic Atoms, Shimoda, Japan, 22-26 Apr 2001. Submitted to Hyperfine Interact.
[27] R. Schiavilla et al., Phys. Rev. C 58, 1263 (1998).
[28] T.S. Park, L.E. Marcucci, R. Schiavilla, M. Viviani, A. Kievsky, S. Rosati, K. Kubodera, D.P. Min, and Manque Rho, nucl-th/0106025, nucl-th/0107012; S. Nakamura, T. Sato, S. Ando, T.S. Park, F. Myhrer, V. Gudkov, and K. Kubodera, Nucl. Phys. A 707, 561 (2002); S. Ando, Y.H. Song, T.S. Park, H.W. Fearing, and K. Kubodera, nucl-th/0206001.
[29] K.I.T. Brown, M.N. Butler, and D.B. Guenther, nucl-th/0207008, submitted to Phys. Rev. C.
[30] E. Pasierb et al., Phys. Rev. Lett. 43, 96 (1979).
[31] F. Reines, H. W. Sobel, and E. Pasierb, Phys. Rev. Lett. 43, 1307 (1980).
[32] F. Reines Nucl. Phys. A396, 469c (1983).
[33] A.G. Vershinsky et al., JETP Lett. 53, 513 (1991).
[34] Yu.V. Kozlov et al., Phys. Atom. Nucl. 63, 1016 (2000).
[35] S.P. Riley, Z.D. Greenwood, W.R. Kropp, L.R. Price, F. Reines, H.W. Sobel, Y. Declais, A. Etenko, and M. Skorokhatov, Phys. Rev. C 59, 1780 (1998); Erratum, October 22, 2001 (unpublished).
[36] K. Schreckenbach, G. Colvin, W. Gelletly and F. Von Feilitzsch, Phys. Lett. B160, 325 (1985); A.A. Hahn, K. Schreckenbach, G. Colvin, B. Krusche, W. Gelletly and F. Von Feilitzsch, Phys. Lett. B218, 365 (1989); P. Vogel and J. Engel, Phys. Rev. D 39, 3378 (1989).
[37] J.F. Beacom and S.J. Parke, Phys. Rev. D 64, 091302 (2001).
[38] Review of Particle Physics, Phys. Rev. D 66, 010001 (2002).
[39] A. Kurylov, private communication.
[40] I.S. Towner, Phys. Rev. C 58 1288 (1998).
[41] A. Kurylov, M.J. Ramsey-Musolf and P. Vogel, *Phys. Rev. C* 65, 055501 (2002).