# Neutrino-induced reactions on $^{12}$C within the continuum random phase approximation

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Motivated by recent experiments we have studied $\nu_e$ and $\nu_\mu$ induced charged- and neutral-current reactions on $^{12}$C within the continuum random phase approximation employing two different residual interactions. We find good agreement with the measured cross sections for the $\nu_e$ reactions, while our calculation significantly differs from recently measured $\nu_\mu$ cross sections. Our calculation indicates that the measurements of the total $^{12}\mathrm{C}(\nu_e, e^-)^{12}\mathrm{N}^*$ cross sections are consistent with the total $^{12}\mathrm{C}(\mu, \nu_\mu)^{12}\mathrm{B}^*$ capture rate.

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Impressive progress has been made in very recent years in experimental studies of neutrino-nucleus scattering. First, experimental groups in Los Alamos [1] and Rutherford (KARMEN collaboration [2]) studied the charged-current excitation of the $^{12}$N ground state in $\nu_e$ scattering from $^{12}$C. Subsequently, the KARMEN collaboration measured the cross section for the $^{12}\mathrm{C}(\nu, \nu')^{12}\mathrm{C}^*$ $(1^+, 1;$ 15.11 MeV) reaction [3], which constitutes the first observation of a neutral-current excitation in nuclei. The observed cross section $\sigma = [11.2\pm1.3(\mathrm{stat.})\pm1.2(\mathrm{syst.})] \times 10^{-42}$ cm$^2$ [4], is compatible with the charged-current measurements and thus confirms the standard model of weak interactions. Very recently a group at Los Alamos studied the inclusive and exclusive cross sections of $(\nu_\mu, \mu^-)$ scattering from $^{12}$C using the pion-in-flight decay beam at LAMPF [5].

In this Brief Report we present a detailed comparison of these data with theoretical calculations performed within the basis of the continuum random phase approximation (RPA). This model has been shown [6,7] to yield a good description of the giant (dipole and spin-dipole) resonances in light nuclei, e.g., in $^{12}$C and $^{16}$O, which are expected to dominate the cross sections in low-energy neutrino-scattering from nuclei. Furthermore, the continuum RPA has been found to satisfactorily reproduce the total muon capture rates in nuclei like $^{12}$C, $^{16}$O, and $^{40}$Ca [8]. Our calculation improves on previous theoretical studies of semileptonic weak interactions in $^{12}$C. This subject was pioneered by Überall *et al.* [9] and by the shell model calculations of Donnelly and Peccei ([10] and references therein). In recent years Mintz and Pourkaviani [11,12] have, in a phenomenological model, used relationships between vector and axial-vector form factors to derive neutrino cross sections from electron scattering data on $^{12}$C.

The continuum RPA has been described in detail in Refs. [7,13], where we particularly follow the model as outlined in Ref. [7]. The latter, however, is improved here as we treat the proton and neutron as individual degrees of freedom. Besides the initial and final nuclear many-body states (in angular momentum representation), the second basic ingredient is the weak Hamiltonian, which we write, according to the standard model, in the usual current-current form. Then neutrino-scattering cross sections and capture rates can be derived in the standard manner by application of the Feynman rules and a multipole expansion of the transition operators as outlined in Ref. [14]. For the nucleon form factors we adopt the values and $Q^2$ dependence from Ref. [15]. To estimate (at least to some extent) the theoretical uncertainties, we applied two different particle-hole interactions in our calculations: the empirical zero-range Landau-Migdal force in the parametrization of Ref. [16] and the (more realistic) finite-range $G$ matrix [17] derived from the Bonn $NN$ potential [18].

First we studied neutrino-induced reactions on $^{12}$C leading to either the $^{12}$N ground state (charged current reaction) or its analogue state in $^{12}$C at 15.11 MeV (neutral current reaction). As a test of our *ab initio* calculation of these neutrino cross sections, we studied the total muon capture rates of the $^{12}$C muonic atom leading to the $^{12}$B ground state $[^{12}\mathrm{C}(\mu^-, \nu_\mu)^{12}\mathrm{B}_{\mathrm{g.s.}}]$ and the $\beta$ decays of the $^{12}$B and $^{12}$N ground state to the $^{12}$C ground state. As the $^{12}$B and $^{12}$N ground states and the 15.11 MeV state in $^{12}$C form an isospin triplet, the muon capture and $\beta$-decay rates are determined by the same nuclear transition matrix elements as the neutrino scattering cross sections.

Two remarks concerning the muon capture and $\beta$-decay calculations are in order. We assume that the muon capture reactions occur from the $(1s)$ orbital of the muonic $^{12}$C atom. In this case the muonic wave function $\Phi_{1s}(r)$ entering into the transition matrix elements varies only slowly over the nuclear volume and therefore (following Ref. [14]) can be well approximated by its averaged value, which we get from a numerical solution of the respective Dirac equation taking finite-size effects of the nucleus into account. The $\beta$ decays of $^{12}$B and $^{12}$N, as well as the charged-current scattering reactions discussed below, are affected by the Coulomb interaction between the final charged lepton and the residual nucleus. We account for this effect in the same manner as outlined in Ref. [19]; i.e., by multiplying capture rates and cross sections with a Coulomb correction factor $F(Z, \epsilon)$, which is derived by numerical solution of the Dirac equation for an extended nuclear charge [20].

Our results for the $\beta$-decay rates of $^{12}$B and $^{12}$N into the $^{12}$C ground state, as well as for the $^{12}C(\mu^-, \nu_\mu)^{12}B_{g.s.}$ capture rate, are compared with the experimental data in Table I. We find that our calculation overestimates the various experimental rates by about a factor of 4. (The fact that our overestimation factors are different for the 3 different processes listed in Table I indicates that isospin symmetry is slightly broken in the $A = 12$ triplet which is mainly due to threshold effects.) To correct for this overestimation, we follow Ref. [21] and rescale, throughout this paper, the matrix elements describing neutrino-induced reactions to the $^{12}$N ground state and the 15.11 MeV state in $^{12}$C by a factor of $\bar{N}^{-1}$, where $\bar{N}$ was set to the mean value of the rescaling factors in Table I ($\bar{N}^2 = 4.13$ for the Landau-Migdal force, $\bar{N}^2 = 3.88$ for the Bonn potential). In the shell model calculation of Ref. [21] a reduction factor of $N^2 = 5.06$ was employed.

The $\nu_e$-scattering experiments [1–3] have been performed with a neutrino beam generated from muons decaying at rest. For comparison with the experimental data we have therefore folded our calculated and rescaled neutrino cross sections with the well-known muon-decay neutrino spectrum (e.g., Ref. [7]). In Table II we summarize our calculated $\nu_e$-induced cross sections leading to the $^{12}$N ground state. The agreement with the experimental data for the charged-current transition is good. The KARMEN collaboration has measured the neutral-current transition to the $^{12}C^*$ (15.11 MeV) state, which, due to the used neutrino beam, is the sum of the $(\nu_e, \nu_e')$ and $(\bar{\nu}_\mu, \bar{\nu}_\mu')$ cross sections. Again the calculated result for the neutral-current excitation agrees nicely with the data (fourth row in Table II). We find that the $\bar{\nu}_\mu$-induced reactions account for approximately 56% of the measured cross section. For completeness the last row of Table II also lists our result for excitations induced by monoenergetic muon-neutrinos ($E_{\nu_\mu} = 29.8$ MeV), which are also present in the KARMEN neutrino beam, but have not been measured yet. Other theoretical estimates of the $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$ cross section [11,21,22], which partly incorporate experimental information from electron scattering, also agree with the neutrino-scattering data and signal the compatibility of the various experimental electroweak probes for this transition.

Possible strange-quark contributions to the weak neutral form factors [15,23], which in general can affect neutral current cross sections, are unimportant for the isovector excitation of the 15.11 MeV $T = 1$ state, as the strange form factors only contribute to isoscalar transitions. The contributions of the strange form factors to the excitation of low-lying $T = 0$ states in $^{12}$C are too small to be experimentally observable.

It is interesting to study the ratio of neutral-current $\sigma_{nc}(\nu_e + \bar{\nu}_\mu)$ to charged-current $\sigma_{cc}(\nu_e)$ cross sections. Fundamentally, this ratio, involving electron and muon neutrinos, allows for a test of the flavor universality incorporated into the standard model of weak interaction and is assumed in all calculations. Practically, the ratio has the advantage that possible uncertainties in the experimental data, arising from the generally hard to determine normalization of the neutrino beam, cancel. Moreover, in our calculation, the ratio is an *ab initio* quantity independent of the unfavorable rescaling. The KARMEN collaboration has determined a ratio $R = 1.37 \pm 0.22$ [4] to be compared with our calculated result $R = 1.13$, as well as with those obtained by Mintz and Pourkaviani, $R = 1.24$ [11,12], and Fukugita *et al.*, $R = 1.07$ [22]. As the KARMEN collaboration continues to take data during the next several years, the expected improvement in the uncertainty will then allow for a more rigorous test of the various theoretical predictions.

In the second part of our study we investigated the transitions to higher states in the continuum, again using the experimentally well-studied muon capture rate as a test case. [Note that the $(1^+, 1;$ 15.11 MeV) state in $^{12}$C lies below the proton emission threshold (15.96 MeV) and therefore was described as a discrete state in our model.] We calculate a total rate for muon capture towards excited states in $^{12}$B of $\lambda^* = 37.20 \times 10^3$ s$^{-1}$ for the Bonn potential and $\lambda^* = 33.26 \times 10^3$ s$^{-1}$ for the Landau-Migdal force, which are both in nice agreement with the experimental value of $(32.8 \pm 0.8) \times 10^3$ s$^{-1}$, derived by subtracting the measured capture rate into the $^{12}$B ground state from the measured total capture rate [24]. Due to this good agreement, it is not necessary to rescale the matrix elements for the continuum states; i.e., all results presented below, except for those leading to the $T = 1$ ground state triplet, are the absolute predictions of our continuum RPA calculation. This is a noticeable difference from the study of Ref. [21] in which the calculated amplitudes for transitions to excited states have been reduced.

The partial muon capture rates of the $^{12}$C atom to the bound excited states of $^{12}$B have been observed experimentally and thus represent another testcase for our calculation. Table III compares our results with the experimental data. Note that in our model all states corre-

TABLE I. $\beta$-decay and muon capture rates for the $A = 12$ system in units of s$^{-1}$. The calculations were performed with the Landau-Migdal force (second column, LM) and the Bonn potential (third column, BP). The experimental data are shown in column 4, where (*) is the mean value (and estimated error) of the measured results given in Refs. [32–35]. The last two columns contain the derived squared rescaling factors of the matrix elements for the two forces.

| Reaction | LM | BP | Experiment | $N^2$ (LM) | $N^2$ (BP) |
|---|---|---|---|---|---|
| $^{12}C(\mu^-, \nu_\mu)^{12}B_{g.s.}$ | 25 400 | 22 780 | 6050±300 (*) | 4.20 | 3.77 |
| $^{12}B_{g.s.}(\beta^-)^{12}C_{g.s.}$ | 128.8 | 123.6 | 33.36±0.13 [36] | 3.86 | 3.71 |
| $^{12}N_{g.s.}(\beta^+)^{12}C_{g.s.}$ | 257.4 | 247.1 | 59.58±0.46 [36] | 4.32 | 4.15 |

TABLE II. Charged- and neutral-current cross sections for neutrino-induced reactions on $^{12}$C leading to the $^{12}$N ground state or its analogue state in $^{12}$C at 15.11 MeV. The calculations were performed with the Landau-Migdal force (second column, LM) and the Bonn potential (third column, BP). The fourth row gives the sum of $\nu_e$- and $\bar{\nu}_\mu$-induced neutral-current cross sections. All cross sections are in units of $10^{-42}$ cm$^2$.

| Reaction | LM | BP | Experiment |
|---|---|---|---|
| $^{12}C(\nu_e, e^-)^{12}N_{g.s.}$ | 9.29 | 9.29 | $10.5 \pm 1.0$(stat.) $\pm$ 1.0(syst.) [1]<br>$8.2 \pm 0.65$(stat.) $\pm$ 0.75(syst.) [4] |
| $^{12}C(\nu_e, \nu_e')^{12}C^*(15.11)$ | 4.65 | 4.65 | |
| $^{12}C(\bar{\nu}_\mu, \bar{\nu}_\mu')^{12}C^*(15.11)$ | 5.91 | 5.88 | |
| $^{12}C(\nu, \nu')^{12}C^*(15.11)$ | 10.56 | 10.53 | $11.2 \pm 1.3$(stat.) $\pm$ 1.2(syst.) [4] |
| $^{12}C(\nu_\mu, \nu_\mu')^{12}C^*(15.11)$ | 2.77 | 2.80 | |

sponding to the excited states in $^{12}$B are above the proton threshold and are thus described as resonances. We have thus derived the partial capture rate to these states by a Breit-Wigner parametrization to the cross section. While both interactions predict the strongest transition to the bound $1^-$ state, they disagree about its strength. While the rate calculated with the finite-range Bonn potential agrees with most of the experimental data, the Landau-Migdal force clearly underestimates this transition. Note that Kobayashi *et al.* [25] also observe a strong dependence of the transition strengths on the interaction as exemplified in Table III by the results obtained for three different interactions [Models (I-III)]. For the transition to the bound $2^-$ state, our results agree better with the data than the previously calculated values. For both interactions, we do not find the excitation of a state that might correspond to the experimentally observed bound $2^+$ state. The entry in Table III was derived as an upper limit from the calculated partial cross section. The observation of this second-forbidden transition is still controversial.

We find total $^{12}C(\nu_e, e^-)^{12}N^*$ cross sections of $6.3 \times 10^{-42}$ cm$^2$ (Bonn potential) and of $5.9 \times 10^{-42}$ cm$^2$ (Landau-Migdal force). These results are in agreement with the measured cross sections of $\sigma = (3.6 \pm 3.7) \times 10^{-42}$ cm$^2$ [26], and $\sigma = (8.6 \pm 1.2 \pm 1.5) \times 10^{-42}$ cm$^2$ [4]. It is important to note that our calculation agrees with the total $^{12}C(\mu, \nu_\mu)^{12}B^*$ capture rate and the total $^{12}C(\nu_e, e^-)^{12}N^*$ cross sections individually suggesting that both data sets are consistent. Based on a shell model approach with empirically reduced transition amplitudes, Donnelly [21] obtained a result of $\sigma = 4.1 \times 10^{-42}$ cm$^2$. It might be interesting to note that the experimental and theoretical results for the inclusive $^{12}C(\nu_e, e^-)X$ cross section [Los Alamos: $(14.1 \pm 2.3) \times 10^{-42}$ cm$^2$ [26]; KARMEN: $(16.8 \pm 1.7) \times 10^{-42}$ cm$^2$ [4]; Donnelly: $14.6 \times 10^{-42}$ cm$^2$ [21]; and this work: $15.2 \times 10^{-42}$ cm$^2$ (Landau-Migdal) and $15.6 \times 10^{-42}$ cm$^2$ (Bonn)] are all in good agreement.

A very recent experiment determined various $\nu_\mu + {}^{12}$C charged-current cross sections using the in-flight pion-decay neutrino source at LAMPF. We have calculated these cross sections within our continuum RPA approach, folding the cross sections with the appropriate LAMPF neutrino beam distribution [5]. The effects of the finite muon mass have been included in our calculation as described in Ref. [14]. We considered contributions arising from an induced-pseudoscalar form factor, where its value was related to the value of the axial vector form factor by the Goldberger-Treiman relation.

TABLE III. Partial muon capture rates for the bound excited states in $^{12}$B [$^{12}C(\mu^-, \nu_\mu)^{12}B^*$] in units of s$^{-1}$, calculated for the Landau-Migdal force (LM) and the Bonn potential (BP). The upper part shows theoretical results, the lower part the measured data. Note that the values marked with $^\#$ were assumed to be 0, as the $0^+ \to 2^+$ transition is second-forbidden. In Ref. [25] three different interactions, labeled Models I–III, were considered, except for the $2^+$ state, which was calculated with yet another interaction.

| | Source | $\omega(1-)$ | $\omega(2-)$ | $\omega(2+)$ | $\omega(^{12}B^*)$ |
|---|---|---|---|---|---|
| Theory | This work (LM) | 220 | 40 | $\leq 1$ | 260 |
| | This work (BP) | 745 | 25 | $\leq 1$ | 770 |
| | Model I [25] | 1400 | 290 | 307 | 2000 |
| | Model II, [25] | 877 | 2210 | 307 | 3394 |
| | Model III, [25] | 1220 | 480 | 307 | 2000 |
| | Ref. [37] | 255 | 423 | 157 | 835 |
| Exp. | Ref. [32] | $720 \pm 175$ | $10 \pm 230$ | $0^\#$ | $760 \pm 140$ |
| | Ref. [33] | $1080 \pm 125$ | $60 \pm 200$ | $0^\#$ | $1140 \pm 235$ |
| | Ref. [34] | $890 \pm 100$ | $170 \pm 240$ | $0^\#$ | $1050 \pm 300$ |
| | Ref. [34] | $700 \pm 400$ | $400 \pm 600$ | $200 \pm 400$ | $1300 \pm 800$ |
| | Ref. [35] | $380 \pm 100$ | $120 \pm 80$ | $270 \pm 100$ | $770 \pm 100$ |

We have calculated the $^{12}C(\nu_\mu,\mu^-)^{12}N_{g.s.}$ cross section applying the same rescaling parameters as defined above. Our values ($\sigma = 0.640 \times 10^{-40}$ cm$^2$ for the Bonn potential and $\sigma = 0.754 \times 10^{-40}$ cm$^2$ for the Landau-Migdal force) are significantly lower than the measured cross section, $\sigma = [17 \pm 8(\text{stat.}) \pm 3(\text{syst.})] \times 10^{-40}$ cm$^2$. To allow the comparison with a previous calculation [21], we have calculated the $^{12}C(\nu_\mu,\mu^-)^{12}N_{g.s.}$ cross section for a fixed neutrino energy of $E_\nu = 250$ MeV. We find $\sigma = 0.684 \times 10^{-40}$ cm$^2$ for the Bonn potential and $\sigma = 0.793 \times 10^{-40}$ cm$^2$ for the Landau-Migdal force in reasonable agreement with the (rescaled) result ($\sigma = 1.3 \times 10^{-40}$ cm$^2$) found in Fig. 6 of Ref. [21], which, however, was obtained in the extreme relativistic limit.

Figure 1 shows the $^{12}C(\nu_\mu,\mu^-)^{12}N$ cross section as a function of neutrino energy and integrated over the final states in $^{12}$N. The continuum RPA result agrees well with the one obtained in the Coulomb-corrected Fermi gas model (see Fig. 12 of Ref. [5]), although it is slightly lower due to the repulsive effects of the residual interaction included in our calculations which tend to shift $T$=1 strength towards higher energies [27,28]. Our cross sections are about twice as large as those empirically estimated by Kim and Mintz [29]. Folding our cross sections with the appropriate LAMPF neutrino spectrum [5], we compute a total cross section of $3.04 \times 10^{-39}$ cm$^2$ for the Bonn potential and of $2.88 \times 10^{-39}$ cm$^2$ for the Landau-Migdal force. Both values are noticeably smaller than the recently measured total cross section of Ref. [5], $\sigma = [15.9 \pm 2.6(\text{stat.}) \pm 3.7(\text{syst.})] \times 10^{-39}$ cm$^2$. Our calculated cross sections are closer to a previous measurement [30], which determined a value of more than two standard deviations smaller than the one in Ref. [5]. Compared to previous theoretical work, our results are somewhat larger than those obtained in a bound-state shell model approach ($1.5 \times 10^{-39}$ cm$^2$) [21].

In Fig. 2 we present our calculated differential $^{12}C(\nu_\mu,\mu^-)^{12}N$ cross section as a function of kinetic muon energy. Our cross section has been integrated over final nuclear states. The calculated spectrum of muon energies does not show the marked depletion of events at higher energies, which is present in the experimental data [5]. In particular, the calculated spectrum has a maximum at noticeably higher energies than the data (at about $E_\mu = 37$ MeV rather than below 20 MeV) and is clearly broader. The continuum RPA muon spectrum agrees well with the results of a Coulomb-corrected Fermi gas calculation [31] in both maximum position and width.

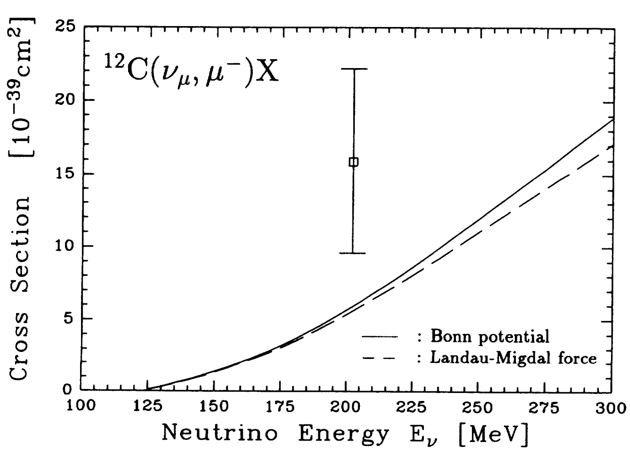


FIG. 1. $^{12}C(\nu_\mu,\mu^-)^{12}N$ cross section as a function of neutrino energy and integrated over final states. The calculation was performed with the Bonn potential (solid curve) and the Landau-Migdal force (dashed).

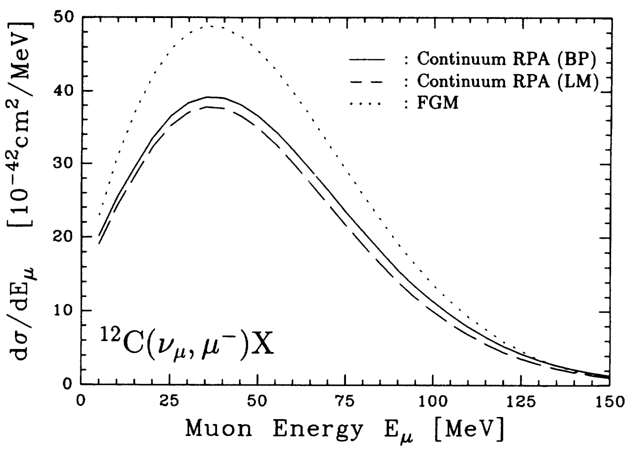


FIG. 2. Differential $^{12}C(\nu_\mu,\mu^-)^{12}N$ cross section as a function of muon energy and integrated over final states. The calculation was performed with the Bonn potential (solid curve) and the Landau-Migdal force (dashed). The dotted curve shows the Coulomb-corrected Fermi gas result [31].

In summary, we have studied various neutrino-induced charged- and neutral-current reactions on $^{12}$C. Generally, our calculation yields good agreement with the stopped-muon beam experiments performed by the KARMEN and LAMPF collaborations, as well as with the measured total and partial muon capture rates. We would like to point out that our study of the $^{12}C(\nu_e,e^-)^{12}N^*$ cross section and of the ratio of neutral-current to charged-current cross sections leading to the $^{12}$N ground state is an *ab initio* calculation and does not involve free parameters. Our calculation suggests that the experimentally difficult measurements of the total $^{12}C(\nu_e,e^-)^{12}N^*$ cross sections are consistent with the total $^{12}C(\mu,\nu_\mu)^{12}B^*$ capture rate.

Nevertheless, our study reveals noticeably different results for the inclusive and exclusive $\nu_\mu$-induced cross sections on $^{12}$C measured recently. As we have performed our continuum RPA calculation for two different residual interactions, which yield similar results to each other and to a Coulomb-corrected Fermi gas study [31], we conclude that the obtained results are not very sensitive to the details of the nuclear model adopted. Thus, we cannot offer an explanation for the failure of our model to reproduce the measured $(\nu_\mu,\mu^-)$ cross section on $^{12}$C.

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[1] R. C. Allen, H. H. Chen, P. J. Doe, R. Hausammann, and W. P. Lee, Phys. Rev. Lett. **64**, 1871 (1990).
[2] G. Drexlin *et al.*, KARMEN collaboration, in *Proceedings of Neutrino Workshop, Heidelberg, 1987*, edited by B. Povh and V. Klapdor (Springer Verlag, Berlin, 1987).
[3] B. Bodmann *et al.*, KARMEN collaboration, Phys. Lett. B **267**, 321 (1991).
[4] J. Kleinfellner *et al.*, KARMEN collaboration, in Proceedings of the XIII International Conference on Particles and Nuclei, Perugia, Italy, 1993, edited by A. Pascolini (in press).
[5] D. D. Koetke, R. Fisk, D. S. Koetke, R. Manweiler, and T. J. Bowles, Phys. Rev. C **46**, 2554 (1992).
[6] S. Krewald, K. Nakayama, and J. Speth, Phys. Rep. **161**, 103 (1988).
[7] E. Kolbe, K. Langanke, S. Krewald, and F. K. Thielemann, Nucl. Phys. **A540**, 599 (1992).
[8] K. Langanke and E. Kolbe, in *Proceedings of the First Symposium on Nuclear Physics in the Universe*, edited by M. W. Guidry and M. R. Strayer (Hilger, London, 1993).
[9] H. Überall, B. A. Lamers, J. B. Langworthy, and F. J. Kelly, Phys. Rev. C **6**, 1911 (1972).
[10] T. W. Donnelly and R. D. Peccei, Phys. Rep. **50**, 1 (1979).
[11] S. L. Mintz and M. Pourkaviani, Phys. Rev. C **40**, 2458 (1989).
[12] S. L. Mintz and M. Pourkaviani, J. Phys. G **16**, 569 (1990).
[13] M. Buballa, S. Drożdż, S. Krewald, and J. Speth, Ann. Phys. **208**, 346 (1991).
[14] J. D. Walecka, in *Muon Physics*, edited by V. W. Hughes and C. S. Wu (Academic, New York, 1975).
[15] E. J. Beise and R. D. McKeown, Comm. Nucl. Part. Phys. **20**, 105 (1991).
[16] G. Co and S. Krewald, Nucl. Phys. **A433**, 392 (1985).
[17] K. Nakayama, S. Drożdż, S. Krewald, and J. Speth, Nucl. Phys. **A470**, 573 (1987).
[18] R. Machleidt, K. Holinde, and Ch. Elster, Phys. Rep. **149**, 1 (1987).
[19] W. C. Haxton, G. J. Stephenson, Jr., and D. Strottman, Phys. Rev. D **25**, 2360 (1982).
[20] H. Behrens and J. Jännecke, *Numerical Tables for Beta-Decay and Electron Capture* (Springer, Berlin, 1969).
[21] J. S. O'Connell, T. W. Donnelly, and J. D. Walecka, Phys. Rev. C **6**, 719 (1972).
[22] M. Fukugita, Y. Kohyama, and K. Kubodera, Phys. Lett. B **212**, 139 (1988).
[23] G. T. Garvey, S. Krewald, E. Kolbe, and K. Langanke, Phys. Lett. B **289**, 249 (1992); G. T. Garvey, E. Kolbe, K. Langanke, and S. Krewald, Phys. Rev. C **48**, 1919 (1993).
[24] T. Suzuki, D. F. Measday, and J. P. Roalsvig, Phys. Rev. C **35**, 2212 (1987).
[25] M. Kobayashi, N. Ohtsuka, H. Ohtsubo, and M. Morita, Nucl. Phys. **A312**, 377 (1978).
[26] D. A. Krakauer, R. L. Talaga, R. C. Allen, H. H. Chen, and R. Hausammann, Phys. Rev. C **45**, 2450 (1992).
[27] F. Osterfeld, Rev. Mod. Phys. **64**, 491 (1992).
[28] J. Engel, E. Kolbe, K. Langanke, and P. Vogel, Phys. Rev. D **48**, 3048 (1993).
[29] C. W. Kim and S. L. Mintz, Phys. Rev. C **31**, 274 (1985).
[30] B. Cortex *et al.*, in *Proceedings of the 1981 Orbis Scientiae, Gauge Theories, Massive Neutrinos, and Proton Decay*, edited by A. Perlmutter (Plenum, New York, 1981).
[31] P. Vogel (private communication).
[32] Y. G. Budgashov *et al.*, JETP **31**, 651 (1970).
[33] M. Giffon *et al.*, Phys. Rev. C **24**, 241 (1981).
[34] G. H. Miller, M. Eckhause, F. R. Kane, P. Martin, and R. E. Welsh, Phys. Lett. **41B**, 50 (1972).
[35] L. Ph. Roesch *et al.*, Phys. Lett. **107B**, 31 (1981).
[36] F. Ajzenberg-Selove, Nucl. Phys. **A506**, 1 (1990).
[37] S. Ciechanowicz, Nucl. Phys. **A372**, 445 (1981).