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Consistent approach to weak interaction rates based on relativistic QRPA

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We present a novel approach to describe charged-current weak interaction rates in nuclei; the weak lepton-hadron interaction is given in the standard current-current form, the nuclear ground state is described in the relativistic Hartree-Bogoliubov model, and the relevant transitions to excited nuclear states are calculated in the relativistic proton-neutron quasiparticle random phase approximation (PN-RQRPA). The PN-RQRPA is formulated in the canonical single-nucleon basis of the relativistic Hartree-Bogoliubov (RHB) model, for an effective Lagrangian characterized by density-dependent meson-nucleon couplings. The initial studies include description of inclusive neutrino-nucleus cross sections for several target nuclei of interest for neutrino detectors. It is shown that model calculations based on PN-RQRPA provide a simultaneous quantitative description of (ν_μ, μ^-) and (ν_e, e^-) reaction cross sections for ^{12}C target nuclei. In addition, the inclusive neutrino-nucleus cross sections were studied for reactions involving supernova neutrinos.

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1. Introduction

Semileptonic weak interactions in nuclei play an important role in nuclear and particle physics, as well as astrophysics. In particular, studies of neutrino-nucleus reactions, charged lepton capture, and beta decay provide not only a knowledge on the relevant processes contributing to the nucleosynthesis in stellar environment, but also useful information for studies of physics beyond the standard model. Since weak interaction rates crucially depend on the structure properties of involved nuclei, it is essential to provide a consistent theoretical framework to describe nuclear ground states and relevant excitations. The formalism of the transition matrix elements important for weak interaction rates has been known for many years [1, 2], however, only recently calculations for open-shell nuclei have been performed using modern effective interactions in description of both nuclear ground and excited states in a consistent way [3, 4].

Recent studies of weak interaction rates at low energies include a variety of microscopic approaches; shell model [5, 6], the random phase approximation (RPA) [7, 4], continuum RPA (CRPA) [8, 9], hybrid model [10, 11], Fermi gas model [12], and particle-number projected quasiparticle RPA(PQRPA) [13]. Since description of high-lying excitations in the shell model necessitates the use of large model spaces that result in computational difficulties, the shell model can be employed only in studies of light and medium-mass nuclei. For systematic studies of weak interaction rates throughout the nuclide chart, microscopic calculations must therefore be performed using models based on the RPA. A fully consistent framework for the description of weak interaction rates in open shell nuclei, based on relativistic Hartree-Bogoliubov (RHB) model and proton-neutron relativistic quasiparticle RPA (PN-RQRPA) has only recently been developed and employed in studies of neutrino-nucleus cross sections [3]. An essential advantage over most current approaches is the use of a single universal effective nuclear interaction in the calculation of both the ground-state properties and excitations of nuclei in various mass regions of the chart of nuclides.

Since nuclei are used as detectors for solar and supernovae neutrinos, as well as in neutrino oscillation experiments, it is essential to achieve a reliable quantitative description of the neutrino response in a fully microscopic theory. Furthermore, description of r-process nucleosynthesis necessitates accurate predictions of neutrino-nucleus cross sections not only in stable nuclei, but also in nuclei away from the valley of β-stability. In these proceedings we show some recent advances on modeling the neutrino-nucleus cross sections in the RHB + PN-RQRPA framework.

2. Neutrino-induced reactions on ^{12}C

In Ref. [3] we have introduced a theory framework for weak interaction rates based on PN-RQRPA to evaluate relevant transitions to excited states. In contrast to the previous study where the extreme relativistic limit has been assumed, in the present approach we employ general expressions for the cross sections based on formalism in Ref. [1]. The reduced matrix elements between the initial and final states are calculated by using the RHB model for the nuclear ground state, and PN-RQRPA to determine excitations of both parities and multipolarities up to J=6. More details about self-consistent relativistic mean-field approach to the description of properties of ground and excited states, not only in stable nuclei but also far from stability, can be found in Refs. [14, 15].

	(ν_μ, μ^-) $\langle\sigma\rangle(10^{-40}cm^2)$	(ν_e, e^-) $\langle\sigma\rangle(10^{-42}cm^2)$
RPA(SIII) [4]	19.23	55.10
QRPA(SIII) [4]	20.29	52.0
CRPA(WS+LM) [10]	18.18	19.28
PQRPA(PIII) [21]		17.54
RPA [22]		13.60
RPA(SGII) [7]	13.5	12.9
RPA(SIII) [7]	14.5	16.5
SM(WS(0+1+2+3)$\hbar\omega$) [23]	13.2	12.3
SM(0$\hbar\omega$ $\times$0.64) [24]	19.2	15.1
SM(HF(0+1+2+3)$\hbar\omega$) [4]	15.18	16.42
PQRPA [13]	12.9	18.6
PN-RQRPA(DD-ME2)	10.97	12.14
Exp.(KARMEN) [19]		14.0$\pm$1.2
Exp.(LSND) [18, 25]	12.4$\pm$0.3$\pm$1.8	13.2$\pm$0.4$\pm$0.6
Exp.(LAMPF) [20]		14.1$\pm$2.3

Table 1: The updated table from Ref. [3] on flux-averaged muon and electron neutrino-nucleus cross sections for the ^{12}C target nucleus. The results of several shell-model, RPA, and QRPA calculations, including the PN-RQRPA(DD-ME2), are compared with available data.

In the present study, for the interaction in the particle-hole channel effective Lagrangians with density-dependent meson-nucleon couplings are used (DD-ME2) [16], and pairing correlations are described by the pairing part of the finite-range Gogny interaction [17]. Both in the particle-hole and pairing channels, the same interactions are used in the RHB equations that determine the canonical quasiparticle basis, and in the matrix equations of the PN-RQRPA. For charged-current reactions, we correct the cross sections for the distortion of the outgoing lepton wave function by the Coulomb field of the daughter nucleus, using the Fermi function for low neutrino energies, and effective momentum approximation at higher energies [4].

We first study electron and muon neutrino-nucleus cross sections for ^{12}C target. This reaction is particularly important because ^{12}C is used in liquid scintillator detectors, and data on the cross section are available from the LSND [18] and KARMEN [19] collaborations, as well as from LAMPF [20]. The results of model calculations can be compared with available data by averaging the cross section over the neutrino flux which depends on the specific neutrino source. For ν_e the Michel flux from the decay at rest (DAR) of μ^+ is used [20], whereas for ν_μ we employ the polynomial fit to the experimental flux obtained from the decay in flight (DIF) of π^+ [18]. In Table 1 we show the updated values of the muon and electron neutrino-nucleus cross sections for ^{12}C, calculated with the PN-RQRPA and averaged over the empirical neutrino fluxes. The results are compared with those of previous theoretical and experimental studies. It is interesting to note that in contrast to most of previous studies, calculations based on PN-RQRPA provide a simultaneous description of both muon and electron neutrino-nucleus cross sections.

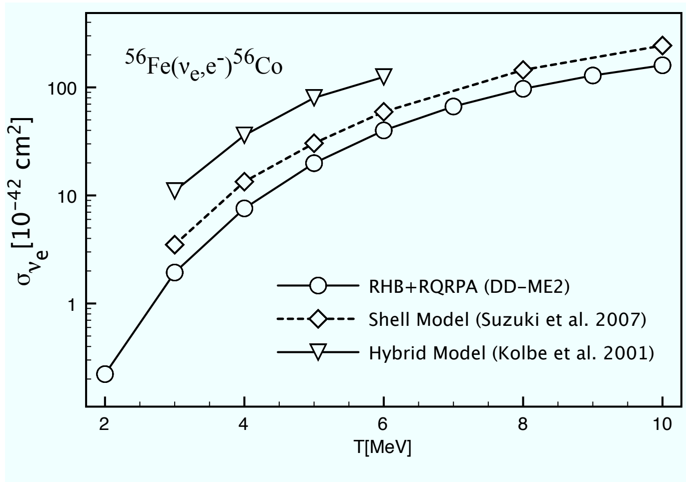

Figure 1: The inclusive neutrino-nucleus cross sections for ^{56}Fe$(\nu_e, e^-)^{56}$Co reaction averaged over the supernova neutrino flux in the range of temperatures T=2-10 MeV. The cross sections based on RHB+RQRPA are compared with the results of shell-model [26] and hybrid model [27].

3. Neutrino-nucleus cross sections for supernova neutrinos

An important application of microscopic models of neutrino-nucleus reactions is the calculation of cross sections for supernova neutrinos. Accurate modeling of reaction rates on nuclei that can be used as targets for the supernova neutrino detectors is, of course, essential for studies of supernova dynamics and, in particular, of weak interaction processes which determine the evolution of a supernova explosion. In this section, we study ^{56}Fe$(\nu_e, e^-)^{56}$Co reaction cross sections averaged over the supernova neutrino flux given by the Fermi-Dirac spectrum [3]. In Fig. 1 we show the corresponding PN-RQRPA cross sections for the reaction evaluated at different temperatures in the interval $T = 2-10$ MeV and chemical potential α=0. We compare the PN-RQRPA results with the shell model [26] and hybrid model [27]. In contrast to the case of ^{16}O target, where we obtained an excellent agreement with the shell model study [3], in the case of ^{56}Fe the PN-RQRPA cross sections are below those of other studies. It is interesting to note that rather low values of cross sections have also been obtained in a very recent study based on projected QRPA [13].

4. Conclusion

A reliable theoretical study of weak interaction rates, both in stable nuclei and in systems far away from the valley of β-stability, necessitates input from fully self-consistent nuclear structure models, which can predict accurate ground-state properties and transition rates to excited states. We have studied muon and electron neutrino-nucleus cross sections in theory framework based on the RHB plus proton-neutron RQRPA. In contrast to previous studies, it is shown that by using the RHB+RQRPA one can obtain a simultaneous quantitative description of (ν_μ, μ^-) and (ν_e, e^-) reaction cross sections for ^{12}C target nuclei. In the case of ^{56}Fe$(\nu_e, e^-)^{56}$Co reaction, the cross sections averaged over supernova neutrino spectra at different temperatures have smaller values than other RPA models, with exception of recently introduced projected QRPA [13]. More detailed studies based on self-consistent nuclear structure models are necessary in order to ensure the accuracy needed for detection of neutrinos and reliable understanding of neutrino nucleosynthesis.

References

[1] O'Connel J S, Donnelly T W, and Walecka J D 1972 *Phys. Rev.* C **6** 719

[2] Walecka J D 1975 *Muon Physics*, edited by V. M. Hughes and C. S. Wu (Academic, New York)

[3] Paar N, Vretenar D, Marketin T, and Ring P 2008 *Phys. Rev.* C**77** 024608

[4] Volpe C, Auerbach N, Colò G, Suzuki T, and Van Giai N 2000 *Phys. Rev.* C **62** 015501

[5] Haxton W C 1987 *Phys. Rev.* D **36** 2283

[6] Suzuki T, Chiba S, Yoshida T, Kajino T, and Otsuka T 2006 *Phys. Rev.* C **74** 034307

[7] Auerbach N, Van Giai N, and Vorov O K 1997 *Phys. Rev.* C **56** R2368

[8] E. Kolbe, K. Langanke, F.-K. Thielemann, and P. Vogel, Phys. Rev. C 52, 3437 (1995).

[9] Jachowicz N, Heyde K, Ryckebusch J, and Rombouts S 2002 *Phys. Rev.* C **65** 025501

[10] Kolbe E, Langanke K, and Vogel P 1999 *Nucl. Phys.* A **652** 91

[11] Kolbe E, Langanke K, Martinez-Pínedo G, and Vogel P 2003 *J. Phys.* G **29** 2569

[12] T. Kuramoto, M. Fukugita, Y. Kohyama, and K. Kubodera, Nucl. Phys. A 512, 711 (1990).

[13] Samana A R, Bertulani C A, and Krmpotić F 2008 `arXiv:0808.1317v1`

[14] Vretenar D, Afanasjev A V, Lalazissis G A, and Ring P 2005 *Phys. Rep.* **409** 101

[15] Paar N, Vretenar D, Khan E, and Colò G 2007 *Rep. Prog. Phys.* **70** 691

[16] Nikšić T, Vretenar D, Finelli P, and Ring P 2002 *Phys. Rev.* C **66** 024306

[17] Berger J F, Girod M, and Gogny D 1991 *Comp. Phys. Comm.* **63** 365

[18] Athanassopoulos C et al. 1998 *Phys. Rev. Lett.* **81** 1774

[19] Bodmann B E et al. 1994 *Phys. Lett.* B **332** 251

[20] Krakauer D A et al. 1992 *Phys. Rev.* C **45** 2450

[21] Krmpotić F, Samana A, and Mariano A 2005 *Phys. Rev.* C **71** 044319

[22] Athar M S, Ahmad S, and Singh S K 2006 *Nucl. Phys.* A **764** 551

[23] Hayes A C and Towner I S 2000 *Phys. Rev.* C **61** 044603

[24] Auerbach N and Brown B A 2002 *Phys. Rev.* C **65** 024322

[25] Auerbach L B et al. 2001 *Phys. Rev.* C **64** 065501

[26] Suzuki T, Chiba S, Yoshida T, Higashiyama K, Honma M, Kajino T, and Otsuka T 2007 *Prog. Part. Nucl. Phys.* **59** 486

[27] Kolbe E and Langanke K 2001 *Phys. Rev.* C **63** 025802