Vol. 40 (2009) *ACTA PHYSICA POLONICA B* No 9

LOW ENERGY NEUTRINO SCATTERING: FROM FUNDAMENTAL INTERACTION STUDIES TO ASTROPHYSICS*

Cristina Volpe

Institut de Physique Nucléaire, CNRS/IN2P3 and University of Paris-XI
91406 Orsay cedex, France

(Received July 8, 2009)

Neutrino scattering at low energies is essential for a variety of timely applications potentially having fundamental implications, *e.g.* unraveling unknown neutrino properties, such as the third neutrino mixing angle, the detection of the diffuse supernova neutrino background, or of cosmological neutrinos and furnishing a new constraint to 2β decay calculations. Here we discuss some applications, the present status and the perspectives.

PACS numbers: 25.30.Pt, 14.60.Pq, 26.50.+x, 11.30.Er

1. Introduction

Core-collapse supernovae are massive stars that undergo gravitational explosions at the end of their life, emitting most of their energy as neutrinos of all flavours in a few second burst. Neutrino scattering at low energy both on nucleons and on nuclei is important for core-collapse supernova physics, not only for the observation of the neutrinos emitted but also for processes occurring within the star like *e.g.* the nucleosynthesis of heavy elements (r-process) [1]. Both the explosion mechanism and the location of the r-process still need to be clarified. Measuring the neutrino luminosity curve produced during a future (extra-)galactic explosion or of the diffuse supernova neutrino background (DSNB), from past explosions, can give essential information both on the explosion, on unknown ν properties and on the star formation rate.

The present upper limits on the DSNB are furnished by the Super-Kamiokande experiment, *i.e.* 1.2 $\bar{\nu}_e$ cm^{-2}s^{-1} [2] and 6.8×10^3 ν_e cm^{-2}s^{-1} from LSD [3], at 90 % C.L. Current theoretical predictions give strong in-

---

[*] Presented at the 45th Winter School in Theoretical Physics "Neutrino Interactions: From Theory to Monte Carlo Simulations", Lądek-Zdrój, Poland, February 2–11, 2009.

dications that future observatories under study [4] (LAGUNA Design Study, in 2008–10 within FP7) should reach a sensitivity sufficient for a discovery potential [5–7]. While (few) hundred events associated to inverse beta-decay are expected in water Cherenkov and scintillator or to neutrino–argon scattering in argon detectors, a few events on oxygen and carbon can give an improved limit compared to the LSD one, as first pointed out in [8].

On the other hand, one should not neglect alternative strategies to the construction of large scale multipurpose (supernova neutrinos, proton decay and CP violation) detectors. For example, as first suggested by Haxton and Johnson [9], the measurement of ^{97}Tc produced by the ν scattering on ^{98}Mo ore can allow the observation of galactic neutrinos. Even though the idea is appealing, a recent re-analysis considering our present knowledge on neutrino oscillations in dense media has shown that two unavoidable requirements are an improved precision on the solar neutrino flux (a significant background) and a precise knowledge of the neutrino–nucleus cross-sections [10].

Serious improvements are currently made in the understanding of core-collapse explosions on one hand and of neutrino propagation in dense media on the other [11, 12]. In particular, a new paradigm has emerged due both to the inclusion of the neutrino–neutrino interaction and of dynamical supernova density profiles with shock waves. While the former engenders collective phenomena [13–15], the latter induces multiple resonances and phase effects [16–19] (for a review see [20]). Recent works have explored possible direct (in an observatory) or indirect (in the star) effects due to the possible existence of CP violation in the lepton sector. They have established that, indeed, there can be CP effects on the neutrino fluxes in a supernova due to loop corrections or physics beyond the Standard Model [21, 22].

In [23] a specificity of lead detectors is used: by using charged-current events in conjunction with one- or two-neutron emission one can distinguish between $\sin^2\theta_{13} \gg 10^{-3}$ and $\ll 10^{-3}$. While the calculation performed needs further refinement, a future lead-based detector — HALO — is now planned at SNOLAB. In [24] it has also been shown that values of the third neutrino mixing angle — within or outside the experimental achievable range — give a characteristic imprint in the positron time signal associated to inverse beta-decay. This calculation has the merit of being the very first one putting together the neutrino–neutrino interaction on one hand and the shock wave effects on the other. In conclusion, the ever increasing level of sophistication of supernova and neutrino propagation modelling as well as of our knowledge of neutrino properties might lead in the future to a concrete use of (relic) supernova neutrinos to unravel supernova physics and/or unknown neutrino properties.

A challenging application of (very) low energy neutrino capture on radioactive nuclei has been proposed very recently, the aim: detecting cosmological neutrinos [25]. Indeed, being non-relativistic at the present epoch, the cross-sections, with no reaction threshold, can strongly be enhanced. Extensive calculations over thousands of nuclei have shown that one might have a significant number of events per year. This idea has been further investigated in [26, 27].

For the case of cosmological neutrinos the momentum transferred to the nucleus is so low that experimental information from beta-decay are used to avoid uncertainties inherent to nuclear structure calculations. However, for neutrinos having energies in the 100 MeV energy range, the calculations present significant variations depending on the details of the model and of the parametrization used.

2. Present status

Computing neutrino–nucleus scattering cross-sections in the several tens of MeV energy range requires modelling of the nuclear degrees of freedom involving either isospin or spin–isospin transition matrix elements. These calculations are sometimes particularly challenging since they involve large model spaces and the inclusion of particular configuration mixings or deformation. Another difficulty comes from the fact that in the measurement: *(i)* one cannot isolate the transition matrix elements except in some specific cases (*e.g.* ground state to ground state transitions); *(ii)* one can only compare with convolved cross-sections. As a consequence, calculations that have significant discrepancies, at a given neutrino energy, can still be in a rather good agreement with the measurements (if the achieved precision is not too good). Note that so far only three nuclei have been studied experimentally, *i.e.* deuteron, carbon and iron. Many calculations exist based on microscopic non-relativistic (such as *e.g.* [28]) or relativistic approaches (see *e.g.* [29]).

The nuclear matrix elements, involved in the cross-sections, are usually known as Fermi-type or Gamow–Teller type transitions. The allowed transitions are rather well under control. However a "quenched" axial-vector coupling constant is still used to account for the difference between experimental and theoretical matrix elements, calculated using various microscopic approaches, such as the Shell Model and the Quasi-particle Random-Phase approximation. The forbidden transitions are still badly known.

The predictions tend to disagree as the neutrino impinging energy increases. In some specific cases, such as the exclusive cross-sections on carbon, the discrepancies have been clarified [30], thanks also to the wealth of experimental data available for this case. However, the inclusive cross-sections are still not all understood. The measurement performed on the iron nucleus, even though it furnishes an important constraint, is not precise enough to discriminate among various theoretical approaches [31]. On the other hand related weak processes, like beta decay and muon capture, or (Fermi and Ikeda) sum-rules help keeping the theoretical ingredients under control. Still, we are far from an accurate treatment of the matrix elements in the nuclei of interest such as ^{12}C, ^{16}O, ^{40}Ar, ^{56}Fe, ^{98}Mo, ^{97}Tc and ^{208}Pb.

Note that a better knowledge of the nuclear response, and of forbidden transition, is particularly important for the double beta-decay searches [32]. In fact, one can show that the nuclear matrix elements involved in the latter are the same as those due to the exchange of a Majorana neutrino. Therefore neutrino–nucleus experiments might furnish a supplementary constraint to the half-life predictions that are still plagued by significant variations. Obviously, since experiments cannot be performed directly on the nuclei of interest, the calculations would benefit from an overall improvement of the nuclear modelisation, *e.g.*, from a step forward on the quenching problem.

3. Perspectives

Experiments with future facilities can shed light on the weak nuclear response in the several tens of MeV energy range. These are: low energy beta-beams [33] — that use the beta-decay of boosted radioactive ions [34] — or facilities exploiting conventional sources (muon decay-at-rest), such as νSNS [35], the European Spallation Source [36] facility, or at the future SPL proton driver. Neutrino–nucleus interaction studies can be realized with detectors based on several nuclei. Although the range of stable nuclei that can be investigated is limited and the cross-section measurements are inclusive, the information obtained with such experiments would constrain the nuclear ingredients of the microscopic approaches like the effective interactions, the model spaces and the configuration mixings included.

The physics potential of low energy neutrinos facilities covers a variety of aspects, from fundamental interactions to nuclear astrophysics and nuclear structure studies. Low energy beta-beams might require either a devoted storage ring [37] or one/two detectors at off-axis [38]. It has been shown that, at such a facility, a measurement of the Weinberg angle at 10% precision level could improve the LNSD measurement by about a factor of 2 [39]. A new test of the Conserved Vector Current hypothesis and in particular of the weak magnetism contribution can also be performed [40]. Other possibilities are the study of non-standard interactions [41] and of coherent scattering [42]. Besides, neutrino–nucleus measurements in the 100 MeV energy range can furnish information on the still badly known forbidden transitions [33,43,44]. In Ref. [45] the possibility of using a combination of beta-beam spectra to analyse core-collapse supernova neutrino fluxes is proposed. Note that most of the ideas proposed for low energy beta-beams (for a review see [46]) are directly applicable to spallation source facilities.

In conclusion, pursuing low energy neutrino scattering studies, either theoretical or experimental, with future spallation sources or low energy beta-beams, can bring essential elements for our understanding of the isospin and spin–isospin nuclear response, for core-collapse supernova physics, for the weak interaction and neutrino physics.

REFERENCES

[1] A.B. Balantekin, G.M. Fuller, *J. Phys. G* **29**, 2513 (2003) `[astro-ph/0309519]`.

[2] M. Malek *et al.*, *Phys. Rev. Lett.* **90**, 061101 (2003) `[hep-ex/0209028]`.

[3] M. Aglietta *et al.*, *Astropart. Phys.* **1**, 1 (1992).

[4] D. Autiero *et al.*, *JCAP* **0711**, 011 (2007) `[arXiv:0705.0116 [hep-ph]]`.

[5] S. Ando, K. Sato, *New J. Phys.* **6**, 170 (2004) `[astro-ph/0410061]`.

[6] C. Lunardini, *Astropart. Phys.* **26**, 190 (2006) `[astro-ph/0509233]`.

[7] S. Horiuchi, J.F. Beacom, E. Dwek, `arXiv:0812.3157 [astro-ph]`.

[8] C. Volpe, J. Welzel, `arXiv:0711.3237 [astro-ph]`.

[9] W.C. Haxton, C.W. Johnson, *Nature* **333**, 325 (1988).

[10] R. Lazauskas, C. Lunardini, C. Volpe, *JCAP* **0904**, 029 (2009) `[arXiv:0901.0581 [astro-ph.SR]]`.

[11] J.T. Pantaleone, *Phys. Lett.* **B287**, 128 (1992).

[12] S. Samuel, *Phys. Rev.* **D48**, 1462 (1993).

[13] H. Duan, G.M. Fuller, Y.Z. Qian, *Phys. Rev.* **D74**, 123004 (2006) `[astro-ph/0511275]`.

[14] S. Hannestad, G.G. Raffelt, G. Sigl, Y.Y.Y. Wong, *Phys. Rev.* **D74**, 105010 (2006); Erratum *Phys. Rev.* **D76**, 029901 (2007) `[astro-ph/0608695]`.

[15] G.G. Raffelt, A.Y. Smirnov, *Phys. Rev.* **D76**, 125008 (2007) `[arXiv:0709.4641 [hep-ph]]`.

[16] R.C. Schirato, G.M. Fuller, `astro-ph/0205390`.

[17] G.L. Fogli, E. Lisi, D. Montanino, A. Mirizzi, *Phys. Rev.* **D68**, 033005 (2003) `[hep-ph/0304056]`.

[18] B. Dasgupta, A. Dighe, *Phys. Rev.* **D75**, 093002 (2007) `[hep-ph/0510219]`.

[19] J.P. Kneller, G.C. McLaughlin, J. Brockman, *Phys. Rev.* **D77**, 045023 (2008) `[arXiv:0705.3835 [astro-ph]]`.

[20] H. Duan, J.P. Kneller, `arXiv:0904.0974 [astro-ph.HE]`.

[21] A.B. Balantekin, J. Gava, C. Volpe, *Phys. Lett.* **B662**, 396 (2008) `[arXiv:0710.3112 [astro-ph]]`.

[22] J. Gava, C. Volpe, *Phys. Rev.* **D78**, 083007 (2008) `[arXiv:0807.3418 [astro-ph]]`.

[23] J. Engel, G.C. McLaughlin, C. Volpe, *Phys. Rev.* **D67**, 013005 (2003) `[hep-ph/0209267]`.

[24] J. Gava, J. Kneller, C. Volpe, G.C. McLaughlin, `arXiv:0902.0317 [hep-ph]`.

[25] A.G. Cocco, G. Mangano, M. Messina, *JCAP* **0706**, 015 (2007) [*J. Phys. Conf. Ser.* **110**, 082014 (2008)] `[hep-ph/0703075]`.

[26] R. Lazauskas, P. Vogel, C. Volpe, *J. Phys. G* **35**, 025001 (2008) `[arXiv:0710.5312 [astro-ph]]`.

[27] M. Blennow, *Phys. Rev.* **D77**, 113014 (2008) `[arXiv:0803.3762 [astro-ph]]`.

[28] O. Civitarese, R.J. Liotta, M.E. Mosquera, *Phys. Rev.* **C78**, 064308 (2008) `[arXiv:0711.4714 [nucl-th]]`.

[29] N. Paar, D. Vretenar, P. Ring, *J. Phys. G* **35**, 014058 (2008); P. Ring, T. Marketin, N. Paar, D. Vretenar *Acta Phys. Pol. B.* **40**, 2537 (2009), this issue.

[30] C. Volpe *et al.*, *Phys. Rev.* **C62**, 015501 (2000) `[nucl-th/0001050]`.

[31] A.R. Samana, C.A. Bertulani, *Phys. Rev.* **C78**, 024312 (2008) `[arXiv:0802.1553 [nucl-th]]`.

[32] C. Volpe, *J. Phys. G* **31**, 903 (2005) `[hep-ph/0501233]`.

[33] C. Volpe, *J. Phys. G* **30**, L1 (2004) `[hep-ph/0303222]`.

[34] P. Zucchelli, *Phys. Lett.* **B532**, 166 (2002).

[35] See `http://www.phy.ornl.gov/nusns/`; I. Stancu, *Acta Phys. Pol. B* **40**, 2653 (2009), this issue.

[36] See `http://ess-neutrons.eu/`

[37] J. Serreau, C. Volpe, *Phys. Rev.* **C70**, 055502 (2004) `[hep-ph/0403293]`.

[38] R. Lazauskas, A.B. Balantekin, J.H. De Jesus, C. Volpe, *Phys. Rev.* **D76**, 053006 (2007) `[hep-ph/0703063]`.

[39] A.B. Balantekin, J.H. de Jesus, C. Volpe, *Phys. Lett.* **B634**, 180 (2006) `[hep-ph/0512310]`.

[40] A.B. Balantekin, J.H. de Jesus, R. Lazauskas, C. Volpe, *Phys. Rev.* **D73**, 073011 (2006) `[hep-ph/0603078]`.

[41] J. Barranco, O.G. Miranda, C.A. Moura, J.W.F. Valle, *Phys. Rev.* **D77**, 093014 (2008) `[arXiv:0711.0698 [hep-ph]]`.

[42] A. Bueno, M.C. Carmona, J. Lozano, S. Navas, *Phys. Rev.* **D74**, 033010 (2006).

[43] G.C. McLaughlin, *Phys. Rev.* **C70**, 045804 (2004) `[nucl-th/0404002]`.

[44] R. Lazauskas, C. Volpe, *Nucl. Phys.* **A792**, 219 (2007) `[arXiv:0704.2724 [nucl-th]]`.

[45] N. Jachowicz, G.C. McLaughlin, *Phys. Rev. Lett.* **96**, 172301 (2006) `[nucl-th/0604046]`.

[46] C. Volpe, *J. Phys. G* **34**, R1 (2007) `[hep-ph/0605033]`.