UNM Final Report
for DOE Topical Collaboration

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During the funding period June 2010 through May 2015 the University of New Mexico (UNM) has successfully hired Huaiyu Duan as a new faculty member with the support from DOE through the Topical Collaboration on Neutrinos and Nucleosynthesis in Hot and Dense Matter (TC). We contributed to TC through our researches and collaborations.

Research

Weak interaction in nuclei and neutrino reactions

During the funding period Allahverdi worked on projects related to weak interactions in nuclei and neutrino reactions, which is one of the focus areas of TC. He participated in an ongoing project on the detection of astrophysical neutrinos in neutrino telescopes such as IceCube. Allahverdi and his collaborators investigated the prospect of detecting bimodal/pseudo-Dirac neutrinos in the next generation of neutrino-less double beta decay experiments and from distant astrophysical sources.

Neutrino flavor transformation in supernovae

Previously Duan & his collaborators have calculated the flavor evolution of the neutronization neutrino burst from O-Ne-Mg core-collapse supernovae by using the single-angle scheme with 3 neutrino flavors (3x3) [*Phys. Rev. Lett.* 100 (2008) 021101]. The single-angle scheme is a widely used approximation to tackle the problem of collective neutrino oscillations in supernovae. In this scheme the flavor evolution of supernova neutrinos are assumed to be the same for different neutrino trajectories. However, the general validity of this scheme has not been fully tested. Duan et al also performed some calculations for different scenarios with the self-consistent but expensive multi-angle scheme with only 2 neutrino flavors (2x2) [*Phys. Rev. Lett.* 97 (2006) 241101].

During the funding period Duan et al finished the numerical code that is capable to do 3x3 multi-angle neutrino oscillations in supernovae. They repeated the simulations for the neutronization neutrino burst from O-Ne-Mg core-collapse supernovae but now with the more sophisticated 3x3 multi-angle scheme. The computations for this scenario yielded results that are indeed qualitatively similar to the 3x3 single-angle ones [Cherry et al, *Phys. Rev. D* 82 (2010) 085025]. However, applying this code to a “standard” late-time supernova environment rendered a very different result [Duan & Friedland, *Phys. Rev. Lett.* 106 (2011) 091101]. An important feature of the late-time supernova environment is that the energy spectra of different neutrino species become very similar as compared to the neutrino spectra at earlier epochs. Duan et al showed that collective neutrino oscillations can start right away in this scenario if the single-angle scheme is adopted. This would potentially invalidate a critical assumption used in the current simulations for supernova explosions and supernova neutrino oscillations. In both kinds of simulations one assumes that neutrinos experience no flavor transformation within the neutrino sphere. Although this assumption remains to be fully tested, our 3x3 multi-angle results suggest that, at least for the scenario that we have investigated, collective neutrino oscillations are suppressed until far away from the neutrino sphere.

Duan and his collaborators further investigated the interplay between the fluctuations in matter densities and the collective neutrino oscillations. They found that a bump in the matter profile of a supernova, such as that at the edge of the He-burning shell of the progenitor star of an O-Ne-Mg supernovae, can change the survival probability of electron flavor neutrinos significantly as they travel through this region if the neutrinos experience collective oscillation in the same region [Cherry et al, *Phys. Rev. D* 84 (2011) 105034; *Phys. Rev. D* 85 (2012) 125010].

Duan and his collaborators also made some preliminary investigations on how neutrino oscillations may occur in the early epochs of Fe core-collapse supernovae. They based their calculations on the snapshots of a two-dimensional (2D) supernova simulation done by the ORNL group (A. Mezzacappa et al). Because the current neutrino simulation code can only handle one-dimensional (1D) supernova model, Duan et al ran the simulations in 1D supernova models which have the same density profiles as those along some characteristic lines of sight in the 2D supernova model. They found that where neutrino oscillations will start can vary significantly along different lines of sight. The implications of this result need to be further investigated.

R-process nucleosynthesis in supernovae

Duan et al computed neutrino energy spectra for different neutrino species in some late-time supernova scenarios as functions of radius by using both the single-angle and multi-angle schemes. These results were fed into another numerical code which is equipped with nuclear-reaction networks and can calculate the yields of various elements in some neutrino-driven wind scenarios [Duan et al, *J. Phys. G 38 (2011) 035201*]. It was found that the neutrino energy spectra generated by single-angle calculations would suppress the production of elements with mass number $A > 140$. This would completely rule out core-collapse supernovae as candidate sites for the *r*-process if it were true. However, because collective neutrino oscillations are suppressed near the neutrino sphere in the multi-angle scheme, the calculations using the neutrino spectra within this more sophisticated scheme showed that heavy elements can indeed be produced. Moreover, the differences in the abundances computed by using neutrino spectra with and without oscillations are significant enough that they cannot be ignored.

Duan also simulated neutrino oscillations in this model at several characteristic epochs and calculated the changes to the neutrino capture rates due to neutrino oscillations throughout the supernova at those epochs. The results imply that collective neutrino oscillations can be suppressed for a fraction of a second after the neutronization neutrino burst. The effects of neutrino oscillations on nucleosynthesis, νp-processes in particular, are being investigated by Duan and his collaborators.

Transport properties of the neutron star crust

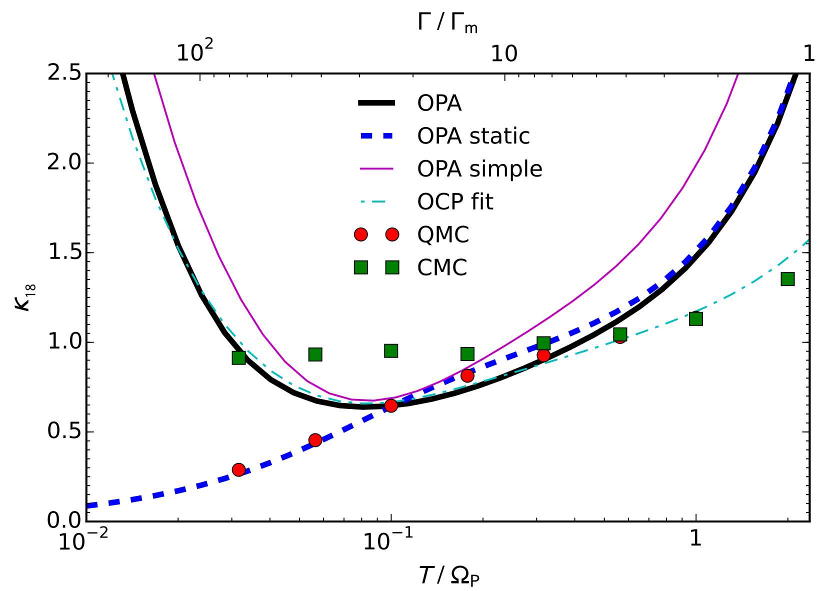

Figure 1: Thermal conductivity of a dense, one-component Coulomb plasma in units of 10^{18} erg cm^{-1}s^{-1}K^{-1} and as a function of temperature T which is measured in terms of the ion plasma frequency Ω_{P}.

Duan, his student Abbar and their collaborators carried out a research on the thermal conductivity of the one-component Coulomb plasma (OCP) under the physical conditions of the neutron star crust. A key quantity used in computing the thermal conductivity of OCP is [Flowers & Itoh, *Astrophys. J.* 206 (1976) 218]

$$S'_\kappa(q) = \int_{-\infty}^{\infty} \langle S'(\omega, \mathbf{q})\rangle_{\hat{\mathbf{q}}} w_\kappa(\omega/T, q)\, \mathrm{d}\omega,$$

where $S'(\omega, \mathbf{q})$ is the inelastic part of the dynamic structure function of the OCP, and w_κ takes into account the quantum statistics of the phonon and electron in OCP. In this study they used several methods to compute the thermal conductivity of OCP:

1. The one-phonon approximation (OPA) method. In this method the exact phonon spectrum of the BCC lattice is first computed by using the dynamic matrix of the lattice. This spectrum is then used to compute $S'(\omega, \mathbf{q})$ assuming that the one-phonon emission and absorption processes dominate.

2. The OPA method with static approximation (OPA static). This method is similar to the OPA method except with the static approximation $S'_\kappa(q) \approx S'(q)$, where $S'_\kappa(q) = \int_{-\infty}^{\infty} \langle S'(\omega, \mathbf{q}) \rangle_{\hat{\mathbf{q}}}\, \mathrm{d}\omega$ is the static structure function.

3. The OPA method with a simple, analytic phonon spectrum (OPA simple).

4. A fitting formula (OCP fit) based on the harmonic approximation which is applicable in a wide range of temperatures.

5. The quantum Monte Carlo technique (QMC) with the static approximation.

6. The classical Monte Carlo technique (CMC) with the static approximation.

A comparison of the thermal conductivity obtained using these methods is shown in Fig. 1. This work showed that $S'(q)$ can be used to compute the conductivity of OCP down to 0.1 of the plasma temperature. This work also established that QMC can be used to compute the thermal conductivity of the Coulomb plasma under the conditions of the neutron star crust.

This work has been submitted to *Phys. Rev. C*. The collaboration is pursuing calculation of the thermal conductivity of the multi-component plasma by using the QMC technique.

Collaborations and interactions

Within the TC platform Duan continued to work on neutrino oscillations with his previous collaborators George Fuller, Yong-Zhong Qian and Joseph Carlson who are also participants of TC. He also started new collaborations Sanjay Reddy and Joseph Carlson on neutron star crust, with Alexander Friedland on neutrino oscillations, and with Gail McLaughlin, Rebecca Surman and Carla Frohlich on nucleosynthesis. Duan also participated in the discussions of the task group for the neutrino burst detection (TG SNsB) within the collaboration effort for the Deep Underground Neutrino Experiment (DUNE), formerly the Long Baseline Neutrino Experiment (LBNE). In particular, he contributed the data generated from the simulations for neutrinos oscillations in supernovae. These data have been used in the detector event rate simulations.

Publications and Talks

PI	publications	preprints	talks
Allahverdi	0	0	1
Duan	5	2	11
Total	5	2	12

Publications and Preprints

1. John F. Cherry, George M. Fuller, J. Carlson, Huaiyu Duan & Yong-Zong Qian, "Multi-angle simulation of flavor evolution in the neutrino neutronization burst from an O-Ne-Mg core-collapse supernova", *Phys. Rev. D* 82 (2010) 085025.

2. Huaiyu Duan & Alexander Friedland, "Self-induced suppression of collective neutrino oscillations in a supernova", *Phys. Rev. Lett.* 106 (2011) 091101.

3. Huaiyu Duan, Alexander Friedland, Gail C. McLaughlin & Rebecca Surman, "The influence of collective neutrino oscillations on a supernova r-process", *J. Phys. G* 38 (2011) 035201.

4. John F. Cherry, Meng-Ru Wu, J. Carlson, Huaiyu Duan, George M. Fuller & Yong-Zhong Qian, "Density fluctuation effects on collective neutrino oscillations in O-Ne-Mg core-collapse supernovae", *Phys. Rev. D* 84 (2011) 105034.

5. John F. Cherry, Meng-Ru Wu, J. Carlson, Huaiyu Duan, George M. Fuller & Yong-Zhong Qian, "Neutrino luminosity and matter-induced modification of collective neutrino flavor oscillations in supernovae", *Phys. Rev. D* 85 (2012) 125010.

6. T. Akiri et al, "The 2010 interim report of the long-baseline neutrino experiment collaboration physics working groups", `arXiv:1110.6249 [hep-ex]`.

7. Sajad Abbar, Joe Carlson, Huaiyu Duan & Sanjay Reddy, "Thermal conductivity of the neutron star crust: A reappraisal", `arXiv:1503.01696` (submitted to *Phys. Rev. C*).

Talks

1. Rouzbeh Allahverdi, "IceCube as a probe for fundamental physics", Mini-Symposium on Nuclear and Neutrino Astrophysics, Los Alamos, March 2010.

2. Huaiyu Duan, "Neutrino oscillations in supernovae", Annual Fall Meeting of the APS Division of Nuclear Physics, Santa Fe, November 2010.

3. Huaiyu Duan, "Inception/suppression of collective neutrino oscillations", Mini-Workshop on Neutron Stars and Neutrinos, Tempe, March 2011.

4. Huaiyu Duan, “The influence of neutrino oscillations on nucleosynthesis”, TC Collaboration Meeting, Los Alamos, June 2011.
5. Huaiyu Duan, “Collective neutrino oscillations in supernovae”, Workshop on Extreme Computing and Its Implications for the Nuclear Physics/Applied Mathematics/Computer Science Interface, Seattle, June 2011.
6. Huaiyu Duan, “Collective neutrino oscillations in supernovae”, Workshop on Implications of Neutrino Flavor Oscillations (INFO), Santa Fe, July 2011.
7. Huaiyu Duan, “Sterile neutrinos and supernovae”, NUPAC Seminar at UNM, Albuquerque, September 2011.
8. Huaiyu Duan, “Supernova neutrinos”, Special Physics Colloquium, Fudan University, May 2012.
9. Huaiyu Duan, “Supernova neutrinos”, High-Energy Physics Forum, Central China Normal University, June 2012.
10. Sajad Abbar, “The static and dynamic structure functions of dense solids and the thermal conductivity of neutron stars”, Topical collaboration meeting, Seattle, January 2013.
11. Sajad Abbar, “Thermal conductivity of the neutron star crust”, APS April Meeting, Savannah, April 2014.
12. Huaiyu Duan, “A sneak peek of collective neutrino oscillations in multi-D models”, Topical Collaboration Meeting, Berkeley, February 2015.

Student	**Entered Grad School**	**Joined Group**	**Degree Program**	**Degree Expected**	**Advisor**
Abbar	Jan. 2011	Jan. 2012	PhD	Aug. 2016	Duan