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Nuclear Physics of Core-Collapse Supernovae

(August 15, 2000 — August 14, 2004)

Yong-Zhong Qian

School of Physics and Astronomy, University of Minnesota
Minneapolis, MN 55455

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Contents

1 Introduction

During the funding period from August 15, 2000 to August 14, 2004, the main foci of my research have been implications of abundances in metal-poor stars for nucleosynthetic yields of supernovae and chemical evolution of the universe, effects of neutrino oscillations and neutrino-nucleus interactions on r-process nucleosynthesis, physical conditions in neutrino-driven winds from proto-neutron stars, neutrino-driven mechanism of supernova explosion, supernova neutrino signals in terrestrial detectors, and constraints on variations of fundamental couplings and astrophysical conditions from properties of nuclear reactions. Personnel (three graduate students and a postdoctoral research associate) involved in my research are listed in section 2. Completed research projects are discussed in section 3. Publications during the funding period are listed in section 4 and oral presentations in section 5. Remarks about the budget are given in section 6.

During the funding period, I have been active in the physics community not only through research and regular university teaching, but also through the following services:

Chair of a summary session at the Pre-Town-Meeting Neutrino Workshop, University of Washington, Seattle, September 2000.

Co-Convener of the Working Group on Solar Neutrinos and Neutrino Astrophysics at the Long Range Plan for Nuclear Science Town Meeting on Astrophysics, Neutrinos, and Symmetries, Oakland, California, November 2000.

Co-Chair of the Local Organizing Committee for the Workshop on "Low Z at Low z and High z: Early Chemical Evolution," Theoretical Physics Institute, University of Minnesota, Minneapolis, March 2002.

Guest Lecturer at the Fourteenth Summer School in Nuclear Physics, Santa Fe, New Mexico, July 2002.

Chair of the Nuclear Astrophysics — Theory Session at the Annual DNP/APS Fall Meeting, East Lansing, Michigan, October 2002.

Member of the Local Organizing Committee for the Workshop on "The Cosmic Microwave Background Radiation and Its Polarization," Theoretical Physics Institute, University of Minnesota, Minneapolis, March 2003.

Member of the Scientific Advisory Committee for the Workshop on "First Stars II," Pennsylvania State University, University Park, May 2003.

Chair of a Session of the Nuclear Astrophysics Workshop at the Annual DNP/APS Fall Meeting, Tucson, Arizona, October 2003.

Co-Organizer of the First Argonne/MSU/JINA/INT RIA Workshop on "The r-Process: The Astrophysical Origin of the Heavy Elements and Related Rare Isotope Accelerator Physics," National Institute for Nuclear Theory, University of Washington, Seattle, January 2004.

Chair of the Session on "Stellar Explosions: Supernovae, Hypernovae, GRBs" at the Workshop on "Chemical Enrichment of the Early Universe," Santa Fe, New Mexico, August 2004.

Co-Organizer of the Program on "The First Stars and Evolution of the Early Universe," National Institute for Nuclear Theory, University of Washington, Seattle, June – July 2006.

2 Personnel

The support and mentoring of postdoctoral research associates is one of my important activities. Whether they eventually obtain a faculty position, work at a national laboratory, or find employment in a private company, these are the scientists of the future. Due to the limited amount of funding, I was able to provide only partial support for a postdoctoral research associate:

• Andrew Steiner (September 2002 — August 2004) He was previously a Ph.D. student in the nuclear theory group at SUNY, Stony Brook and received the Dissertation in Nuclear Physics Award from the APS in 2004. He was also supported by the DOE grant to the nuclear theory group at Minnesota. He is now a postdoc with T-16, Los Alamos National Laboratory.

The education and training of graduate students is another of my important activities. Three graduate students at the top of their respective class have been working with me. They are very valuable to my research program. Again due to the limited amount of funding, I was able to provide only partial support for these students:

• Huaiyu Duan (Began research with me in 2000, Ph.D. awarded in the fall of 2004. Thesis title: "Neutrino Processes in Strong Magnetic Fields and Implications for Supernova Dynamics." He was supported by the DOE grant to the nuclear theory group at Minnesota and is now a postdoc with George Fuller at Department of

Physics, University of California, San Diego.)

• Yu Lu (Began research with me in 2001, ABD status: All But Dissertation.)

• He Ning (Began research with me in 2002, ABD status.)

3 Highlights of Completed Work

During the funding period from August 15, 2000 to August 14, 2004, I have published 20 papers (including 5 Letters and 1 major invited review) in refereed journals, 2 invited contributions in conference proceedings, and 1 invited article in Physics Today. I also coedited the Proceedings of the First Argonne/MSU/JINA/INT RIA Workshop on "The r-Process: The Astrophysical Origin of the Heavy Elements and Related Rare Isotope Accelerator Physics" with E. Rehm, H. Schatz, and F.-K. Thielemann. [4.5.1] Some research highlights are given below.

• In collaboration with Wasserburg (Caltech), I developed a detailed model for understanding the abundances of various elements in metal-poor stars. This model assumed that there are only two distinct kinds of yield patterns provided by supernovae and an initial inventory of metals provided by the first generations of very massive stars. Given the abundances of Eu and Fe, the abundances of the other elements could be calculated for any star from this model. [4.1.3], [4.1.5], [4.1.6] The predictions based on this model have been confirmed by several observational groups. [4.2.2]

• In collaboration with Sargent and Wasserburg (both of Caltech), I found a connection between the abundances in metal-poor stars of the Galaxy and those in the intergalactic medium over a broad range of redshift. This connection supports the proposal by Wasserburg and me that the first generations of very massive stars provided an initial inventory of metals to the universe. [4.1.2], [4.1.7]

• Wasserburg (Caltech) and I studied the chemical evolution of galaxies based on the standard model of cosmological structure formation. In this model, cold dark matter first collapsed to form small halos, taking along baryonic gas. Halos then grow through infall of dark matter and baryonic gas. Considering both elemental production by supernovae and dilution of chemical enrichment by infall of gas in a halo, we provided a simple explanation for the slow evolution of Fe abundances with redshift in individual protogalaxies and the large scatter in Fe abundances for the protogalaxies sampled at any given redshift. [4.1.13], [4.1.17]

• I showed that the observational data on abundances of neutron-capture elements in metal-poor stars can be explained by a model of diverse supernova sources for the r-process. In this model, the high frequency H events produce the neutron-capture elements with $A > 130$ such as Eu by the r-process but no Fe, whereas the low frequency L events produce Fe and the neutron-capture elements with $A \leq 130$ such as Ag. The frequencies of H and L events as well as their elemental yields can be calculated from the solar system data on extinct radioactivities and stable nuclei. This model then predicts the dispersion in the Eu abundance at a given Fe abundance and the mean trend for evolution of Eu with Fe, which are in good agreement with the data. [4.1.4]

• I proposed a novel scenario where neutrino-induced fission is responsible for producing the abundance patterns of heavy elements observed in metal-poor stars. In this scenario, neutrino interaction with the progenitor nuclei produced by rapid neutron capture (r-process) excites these nuclei to $\sim$ 20 MeV above the ground state, thereby causing them to fission. A detailed study of this scenario may help establish supernovae as the site of the r-process and provide a means to explore neutrino physics. [4.1.8] I reviewed (for Prog. Part. Nucl. Phys.) progress in the understanding of the r-process over the last decade in the areas of parametric studies, theoretical models, and observations. [4.1.10] I also wrote three shorter reviews on the r-process [4.1.1], [4.2.3], [4.3.1] and suggested the needs for nuclear data in studies of the r-process. [4.2.1]

• Based on observations of metal-poor stars, especially the work by Cohen (Caltech) and Christlieb (Uppsala) [4.1.11], Wasserburg (Caltech) and I proposed that low-mass supernovae and accretion-induced collapse (AIC) of white dwarfs are the dominant sites for the r-process. We also suggested observational tests for these sites. In particular, as AIC events have neutrino signals similar to regular supernovae but lack significant optical display, detection of neutrinos from an AIC event in the Galaxy would be crucial in establishing the r-process sites. [4.1.12]

• In collaboration with Argast, Samland, Thielemann (all of Basel), I showed that current observations of metal-poor stars can be accounted for if supernovae are the major site for the r-process. However, neutron star mergers are ruled out as a major site. Due to the extremely low frequency of neutron star mergers, they could not provide r-process elements to stars formed at early times with low Fe abundances. Further, each neutron star merger must produce a lot of r-process elements in order to be a major site. This would result in too much of these elements in stars formed at later times with higher Fe abundances. This work provides strong motivation for further studies of r-process nucleosynthesis in supernovae. [4.1.15]

• Steiner and I studied the neutrino-driven wind from a protoneutron star using a

numerical code that follows the evolution of the velocity, density, temperature, and electron fraction in the wind. We examined the conditions for r-process nucleosynthesis in the wind in terms of the mass, radius, and neutrino emission characteristics of the protoneutron star. [4.3.2]

• Duan and I calculated rates for neutrino and electron capture on nucleons in strong magnetic fields that may exist near the protoneutron star produced in a supernova. We found that strong magnetic fields introduce significant angular dependence in the neutrino capture rate by polarizing the nucleon spin and substantially reduce the electron capture rate by quantizing the electron motion into Landau levels. As neutrino capture provides heating and electron capture provides cooling behind the supernova shock, strong magnetic fields can have important effects on the explosion mechanism by changing the capture rates. [4.1.16]

• In collaboration with Olive, Pospelov (University of Vicotria), Coc (Orsay), Cassé, Vangioni-Flam (CNRS, Paris), and Manhès (LGC, Paris), I reconsidered several bounds on the variation of the fine-structure constant in models where all gauge and Yukawa couplings vary in an interdependent manner, as would be expected in unified theories. In particular, we reexamined the bounds established by the natural fission reactor at Oklo from the resonant neutron-capture cross section of ^{149}Sm. By imposing variations in the QCD energy scale and the quark masses, as dictated by unified theories, the bound on the variation of the fine-structure constant was improved by about 2 orders of magnitudes. In addition, we considered possible bounds on variations due to the effect on long-lived α- and β-decay isotopes, particularly ^{147}Sm and ^{187}Re. We obtained a strong constraint on the variation of the fine-structure constant, comparable to that of Oklo but extending to a higher redshift that borders the range over which significant variations have been claimed based on studies of quasar absorption spectra. [4.1.9], [4.1.14] Olive and I also wrote an invited review article on variations of fundamental constants for Physics Today. [4.4.1]

4 Publications

4.1 Publications in Refereed Journals

1. "Neutrinos and the Supernova Origin of the Elements," Nucl. Phys. B (Proc. Suppl.) **91**, 345 (2001) [Y.-Z. Qian].

2. "Evolution of O Abundance Relative to Fe," Astrophys. J. **549**, 337 (2001) [Y.-Z. Qian and G. J. Wasserburg].

3. "Abundances in the Uranium-Rich Star CS 31082-001," Astrophys. J. Lett.

552, L55 (2001) [Y.-Z. Qian and G. J. Wasserburg].

4. "Diverse Supernova Sources for the r-Process and Abundances in Metal-Poor Stars," Astrophys. J. Lett. **552**, L117 (2001) [Y.-Z. Qian].

5. "A Model for Abundances in Metal-Poor Stars," Astrophys. J. **559**, 925 (2001) [Y.-Z. Qian and G. J. Wasserburg].

6. "Determination of Nucleosynthetic Yields of Supernovae and Very Massive Stars from Abundances in Metal-Poor Stars," Astrophys. J. **567**, 515 (2002) [Y.-Z. Qian and G. J. Wasserburg].

7. "The Prompt Inventory from Very Massive Stars and Elemental Abundances in Lyα Systems," Astrophys. J. Lett. **569**, L61 (2002) [Y.-Z. Qian, W. L. W. Sargent, and G. J. Wasserburg].

8. "Neutrino-Induced Fission and r-Process Nucleosynthesis," Astrophys. J. Lett. **569**, L103 (2002) [Y.-Z. Qian].

9. "Constraints on the Variations of the Fundamental Couplings," Phys. Rev. D **66**, 045022, (2002) [K. A. Olive, M. Pospelov, Y.-Z. Qian, A. Coc, M. Cassé, and E. Vangioni-Flam].

10. "The Origin of the Heavy Elements: Recent Progress in the Understanding of the r-Process," Prog. Part. Nucl. Phys. **50**, 153 (2003) [Y.-Z. Qian].

11. "Abundance Analysis of HE 2148-1247, A Star with Extremely Enhanced Neutron Capture Elements," Astrophys. J. **588**, 1082 (2003) [J. G. Cohen, N. Christlieb, Y.-Z. Qian, and G. J. Wasserburg].

12. "Stellar Sources for Heavy r-Process Nuclei," Astrophys. J. **588**, 1099 (2003) [Y.-Z. Qian and G. J. Wasserburg].

13. "Hierarchical Structure Formation and Chemical Evolution of Damped Lyα Systems," Astrophys. J. Lett. **596**, L9 (2003) [Y.-Z. Qian and G. J. Wasserburg].

14. "A Re-examination of the ^{187}Re Bound on the Variation of Fundamental Couplings," Phys. Rev. D **69**, 027701 (2004) [K. A. Olive, M. Pospelov, Y.-Z. Qian, G. Manhès, E. Vangioni-Flam, A. Coc, and M. Cassé].

15. "Neutron Star Mergers versus Core-Collapse Supernovae as Dominant r-Process Sites in the Early Galaxy," Astron. Astrophys. **416**, 997 (2004) [D. Argast, M. Samland, F.-K. Thielemann, and Y.-Z. Qian].

16. "Neutrino Processes in Strong Magnetic Fields and Implications for Supernova Dynamics," Phys. Rev. D **69**, 123004 (2004) [H. Duan and Y.-Z. Qian].

17. "Hierarchical Structure Formation and Chemical Evolution of Galaxies," Astrophys. J. **612**, 615 (2004) [Y.-Z. Qian and G. J. Wasserburg].

4.2 Papers in Press

1. "The r-Process: Recent Progress and Needs for Nuclear Data," Nucl. Phys. A, in press (2004) [Y.-Z. Qian].

2. "The Hamburg/ESO r-Process Enhanced Star Survey (HERES). I. Project Discription and Discovery of CS 29497–004, A Star with Strong Enhancement of Neutron-Capture Elements," Astron. Astrophys., in press (2004) [N. Christlieb, T. C. Beers, P. S. Barklem, M. Bessell, V. Hill, J. Holmberg, A. J. Korn, B. Marsteller, L. Mashonkina, Y.-Z. Qian, S. Rossi, G. J. Wasserburg, F.-J. Zickgraf, K.-L. Kratz, B. Nordström, B. Pfeiffer, and J. Rhee].

3. "Nuclear Physics and Astrophysics of the r-Process," Nucl. Phys. A, in press (2004) [Y.-Z. Qian].

4.3 Publications in Conference Proceedings

1. "The r-Process: Current Understanding and Future Tests," in "The r-Process: the Astrophysical Origin of the Heavy Elements and Related Rare Isotope Accelerator Physics," eds. Y.-Z. Qian, E. Rehm, H. Schatz, and F.-K. Thielemann, World Scientific, Singapore (2004) p. 147 [Y.-Z. Qian].

2. "r-Process Nucleosynthesis in Neutrino-Driven Winds: Treatment of the Injection Region and Requirements on Neutrino Emission," in "The r-Process: the Astrophysical Origin of the Heavy Elements and Related Rare Isotope Accelerator Physics," eds. Y.-Z. Qian, E. Rehm, H. Schatz, and F.-K. Thielemann, World Scientific, Singapore (2004) p. 176 [A. W. Steiner and Y.-Z. Qian].

4.4 Invited Article in Physics Today

1. "Were Fundamental Constants Different in the Past?" Physics Today, October 2004, p. 40 [K. A. Olive and Y.-Z. Qian].

4.5 Book

1. "The r-Process: the Astrophysical Origin of the Heavy Elements and Related Rare Isotope Accelerator Physics," eds. Y.-Z. Qian, E. Rehm, H. Schatz, and F.-K. Thielemann, World Scientific, Singapore (2004).

5 Oral Presentations

5.1 Y.-Z. Qian

1. Invited Colloquium (60 min) Department of Astronomy, University of Minnesota: "From Rocks, Stars, and Galaxies to Neutrinos, Nuclei, and Nuclear Matter," September 2000.

2. Invited Colloquium (60 min) Physics Division, Argonne National Laboratory: "Recent Progress in Understanding Nucleosynthesis via Rapid Neutron Capture: from Rocks, Stars, and Galaxies to Neutrinos, Nuclei, and Nuclear Matter," September 2000.

3. Invited Talk (15 min) Long Range Plan for Nuclear Science Town Meeting on Nuclear Structure and Astrophysics, Oakland, California: "r-Process Nucleosynthesis and Possible Advances with RIA," November 2000.

4. Invited Seminar (60 min) Kellogg Radiation Laboratory, California Institute of Technology: "Recent Progress in Understanding Nucleosynthesis via Rapid Neutron Capture: from Rocks, Stars, and Galaxies to Neutrinos, Nuclei, and Nuclear Matter," January 2001.

5. Invited Talk (20 min) Symposium on Physics Potential of Supernova Neutrino Detection, Marina del Rey, California: "Rocks, Stars, and Neutrinos," February 2001.

6. Invited Seminar (60 min) National Superconducting Cyclotron Laboratory, Michigan State University: "Recent Progress in Understanding r-Process Nucleosynthesis: from Rocks and Stars to Neutrinos and Nuclei," February 2001.

7. Invited Talk (40 min) International Symposium on Nuclear Astrophysics, GSI-Darmstadt, Germany: "The Mystery of the r-Process Site," May 2001.

8. Invited Seminar (60 min) T-16, Theoretical Division, Los Alamos National Laboratory: "The Mystery of the Site for r-Process Nucleosynthesis," May 2001.

9. Invited Nuclear and Particle Physics Seminar (30 min) Los Alamos National Laboratory: "Rocks with a View of the Bigger Universe," June 2001.

10. Invited Seminar (60 min) Theoretical Astrophysics Group, Fermilab: "Rocks, Stars, and Galaxies: New Insights into Chemical Evolution of the Universe," February 2002.

11. Invited Talk (35 min) TPI Workshop on Low Z at Low z and High z: Early Chemical Evolution, Minneapolis, Minnesota: "Observational Implications for the r-Process," March 2002.

12. Invited Talk (30 min) Stellar Abundances & Nucleosynthesis Conference, Seattle, Washington: "Recent Progress in Theoretical Studies of the r-Process," March 2002.

13. Invited Talk (30 min) CUSPEA Conference on Physics in the 21st Century, Beijing, China: "Neutrinos and the Origin of the Elements," June 2002.

14. Invited Seminar (60 min) School of Science, University of Science and Technology of China, Hefei, China: "The Future of Nuclear Physics: Challenges and Opportunities," June 2002.

15. Invited Seminar (60 min) Department of Astronomy and Applied Physics, University of Science and Technology of China, Hefei, China: "The First Stars and Chemical Evolution of the Universe," June 2002.

16. Invited Talk (60 min) Theoretical Division, Los Alamos National Laboratory: "The Origins of the Elements: A Phenomenological Approach and Implications for Nucleosynthesis," July 2002.

17. Invited Lecture (60 min) Fourteenth Summer School in Nuclear Physics, Santa Fe, New Mexico: "Rocks with a View of the Universe: from Neutrinos and Nuclei to Stars and Galaxies," July 2002.

18. Invited Talk (40 min) Annual DNP/APS Fall Meeting, East Lansing, Michigan: "Neutrinos and the Origin of the Elements: from the Big Bang to Supernovae," October 2002.

19. Invited Talk (45 min) KITP Conference on "Neutrinos: Data, Cosmos, and Planck Scale," University of California, Santa Barbara: "Neutrinos and the Origin of the Elements: from the Big Bang to Supernovae," March 2003.

20. Invited Talk (60 min) RIA Symposium, Argonne National Laboratory: "The Origin of the Heavy Elements: Recent Progress in Understanding the r-Process," May 2003.

21. Invited Talk (30 min) Workshop on "First Stars II," Penn State University, University Park: "Abundances in Metal-Poor Stars: Implications for the Origin of the Heavy Elements and Cosmology," May 2003.

22. Invited Talk (30 min) Workshop on "Physics and Astrophysics of Neutron Stars," Santa Fe, New Mexico: "Accretion-Induced Collapse of a White Dwarf into a Neutron Star and Heavy Element Nucleosynthesis," July 2003.

23. Invited Talk (30 min) Sixth International Conference on Radioactive Nuclear Beams, Argonne National Laboratory: "The r-Process: Recent Progress and Needs for Nuclear Data," September 2003.

24. Invited Talk (30 min) Nuclear Astrophysics Workshop, Annual DNP/APS Fall Meeting, Tucson, Arizona: "The r-Process Elements: Physics, Origin, and RIA," October 2003.

25. Invited Talk (35 min) First Argonne/MSU/JINA/INT RIA Workshop on "The r-Process: The Astrophysical Origin of the Heavy Elements and Related Rare Isotope Accelerator Physics," University of Washington, Seattle: "The r-Process: Current Understanding and Future Tests," January 2004.

26. Invited Colloquium (30 min) Department of Astronomy, California Institute of Technology: "Chemical Evolution of Galaxies and Enrichment of the Intergalactic Medium," May 2004.

27. Invited Talk (30 min) Topical Session on "Detecting the First Stars and AGN," 204th AAS meeting, Denver, Colorado: "Metallicity Signatures from the First Stars," June 2004.

28. Invited Talk (30 min) Topical Conference on Nuclear Astrophysics, 22nd International Nuclear Physics Conference (INPC2004), Göteborg, Sweden: "Nuclear Physics and Astrophysics of the r-Process," June 2004.

29. Invited Talk (30 min) INT Workshop on "Supernova Theory and Nucleosynthesis," University of Washington, Seattle: "The r-Process: Where Do We Stand?" July 2004.

30. Invited Talk (30 min) Workshop on "Chemical Enrichment of the Early Universe," Santa Fe, New Mexico: "r-Process Nucleosynthesis in the Early Universe and Cosmological Implications," August 2004.

5.2 A. Steiner

1. Nuclear Physics Seminar (60 min) School of Physics and Astronomy, University of Minnesota: "Color-Neutral Superconducting Quark Matter," September 2002.

2. Cosmology Lunch Seminar (60 min) School of Physics and Astronomy, University of Minnesota: "Supernova, Gamma-Ray Bursts, and Stellar Rotation," March 2003.

3. Invited Talk (30 min) Workshop on "Physics and Astrophysics of Neutron Stars," Santa Fe, New Mexico: "Neutrino-Driven Winds Revisited: The Production of r-Process Nuclei," July 2003.

4. Invited Talk (60 min) Los Alamos National Laboratory: "Nuclear Astrophysics in Two Acts: Neutrino-Driven Winds and the Nuclear Symmetry Energy," December 2003.

5. Invited Talk (35 min) First Argonne/MSU/JINA/INT RIA Workshop on "The r-Process: The Astrophysical Origin of the Heavy Elements and Related Rare Isotope Accelerator Physics," University of Washington, Seattle: "Neutrino-Driven Winds Revisited: The Production of r-Process Nuclei," January 2004.

6. Invited Talk (60 min) Argonne National Laboratory: "Nuclear Astrophysics in Two Acts: Neutrino-Driven Winds and the Nuclear Symmetry Energy," January 2004.

7. Invited Talk (60 min) TRIUMF: "Nuclear Astrophysics in Two Acts: Neutrino-Driven Winds and the Nuclear Symmetry Energy," February 2004.

8. Dissertation in Nuclear Physics Award Talk (35 min) Spring Meeting of the APS: "The Microphysics, Evolution, and Observations of Quarks in Neutron Stars," May 2004.

5.3 H. Duan

1. Invited Talk (30 min) Mini-Workshop on Heavy Ion Reaction Dynamics, University of Minnesota: "Neutrino Flavor Mixing in Supernovae as a Transport Problem," November 2000.

2. Student Talk (30 min) Fourteenth Summer School in Nuclear Physics, Santa Fe, New Mexico: "Neutrino-Neutrino Interactions in Supernovae," July 2002.

3. Cosmology Lunch Seminar (60 min) School of Physics and Astronomy, University of Minnesota: "Evidence for Neutrino Flavor Transformation from SNO," September 2002.

4. Cosmology Lunch Seminar (60 min) School of Physics and Astronomy, University of Minnesota: "Is Primordial ^{4}He Truly from Big Bang?" February 2003.

5. Triangle Nuclear Theory Colloquium (60 min) North Carolina State University: "Neutrino Processes in Strong Magnetic Fields and Supernova Physics," April 2004.

6. Invited Talk (20 min) INT Workshop on "Open Issues in Understanding Core Collapse Supernovae," University of Washington, Seattle: "Neutrino Processes in Strong Magnetic Fields," June 2004.

5.4 Y. Lu

1. Cosmology Lunch Seminar (60 min) School of Physics and Astronomy, University of Minnesota: "Detection of Supernova Neutrinos by Neutrino-Proton Elastic Scattering," October 2002.

2. Cosmology Lunch Seminar (60 min) School of Physics and Astronomy, University of Minnesota: "Relic Supernova Neutrinos and Neutrino Oscillations," March 2003.

5.5 H. Ning

1. Cosmology Lunch Seminar (60 min) School of Physics and Astronomy, University of Minnesota: "Neutrino Mixing in the Early Universe," March 2003.

6 Budget Note

The entire grant of $200,000 was used up by the end of the funding period.