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# NUCLEAR PHYSICS AND ASTROPHYSICS

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Progress Report

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**Abstract**

We have investigated a variety of research topics on the interface of nuclear physics and astrophysics during the past year. We have continued our study of dihyperon states in dense matter and have started to make a connection between their properties in the core of neutron stars with the ongoing experimental searches at Brookhaven National Laboratory. We started to build a scenario for the origin of gamma-ray bursts using the conversion of neutron stars to strange stars close to an active galactic nucleous. We have been reconsidering the constraints due to neutron star cooling rates on the equation of state for high density matter in the light of recent findings which show that the faster direct Urca cooling process is possible for a range of nuclear compositions. We have developed a model for the formation of primordial magnetic fields due to the dynamics of the quark-hadron phase transition. Encouraged by the most recent observational developments, we have investigated the possible origin of the boron and beryllium abundances. We have greatly improved the calculations of the primordial abundances of these elements by augmenting the reaction networks and by updating the most recent experimental nuclear reaction rates. Our calculations have shown that the primordial abundances are much higher than previously thought but that the observed abundances cannot be explained by primordial sources alone. We have also studied the origin of the the boron and beryllium abundances due to cosmic ray spallation. Finally, we have continued to address the solar neutrino problem by investigating the impact of astrophysical uncertainties on the MSW solution for a full three-family treatment of MSW mixing.

## Description of Research Progress

We summarize below some of the research achievements on the interface of nuclear physics and astrophysics done over the past year by D. N. Schramm (P.I.), A. V. Olinto (co-P.I.), D. Thomas (research associate), and B. Field, B. Cheng, and X. Shi (graduate students), under the DOE grant no. DE-FG02-90ER40606 at the University of Chicago. We keep references to a minimum, mostly specifying work done by our group.

We have been very encouraged by the recent developments on experimental proposals and experiments underway which will search for different forms of nuclear states (H. Crawford, 1992). Brookhaven National Laboratory and CERN have started a series of experiments (at BNL: E814, E858, E878, E864, E911; and at CERN: NA-38, P259) geared towards constraining the properties of dihyperons (like the H-particle) and the search for strangelets (small baryon number unstable states of strange matter). Results from these experiments will be of great interest to some of our research efforts.

As we have mentioned in our previous report, Olinto and collaborators have investigated some of the implications of baryonic condensates on neutron star structure. The simplest example of such condensates arises from the possible existence of a metastable dibaryon state, called the H-particle (Jaffe 1977). Olinto, Haensel, and Frieman (1991) have shown that if these states exist, they will be an important component of neutron stars for a wide range of the possible H parameters. Baryonic condensates significantly soften the equation of state of neutron stars and enhance the neutrino emissivity of nuclear matter which accelerates the cooling of neutron stars. We also are able to constrain the parameters of dibaryon states by requiring that they do not destabilize a $1.4M_{\odot}$ neutron star. We have explored the range of uncertainties generated by the range in possible nuclear equations of state. We are now trying to relate the astrophysical constraints to the parameters that experiments can test.

On the subject of strange matter, we have been studying the likelyhood of metastable strangelets being formed at temperatures below the formation of a quark-gluon plasma, and how such droplet could survive long enough to reach any detector. The problem of strangelet longevity and how strange matter lumps interact have an interesting astrophysical implication. The question of whether every young neutron stars would have been converted to strange stars if there is a small fraction of strange stars in the universe depends on large lumps of strange matter (of baryon number $\sim 10^{49}$ ) dissociating into much smaller ones (of baryon number $\sim 10^6$). The issue of an efficient strange matter contamination was studied by Friedman and Caldwell (1991). They assumed that large chunks of strange matter tidally disrupted at the end of a binary two strange stars system break down into much smaller ones, making the contamination of supernova progenitor stars more efficient. If the tidally disrupted chunks are not dissociated effectively, strange stars and neutron stars can coexist.

A very interesting puzzle in high energy astrophysics today is the origin of gamma-ray bursts. R. Epstein and Olinto are working on a model that might get the very sought after spectrum of gamma-ray bursts. In this model, a very energetic event happens in the neighbourhood of an active galactic nucleous giving rise to a compton reflection of the AGN spectrum by a highly relativistic plasma ($\gamma \sim 10^3$). An example of the kind of event that would be able to trigger such a boost of the spectrum could be the conversion of a neutron star to a strange star. Some other attempts of explaining gamma-ray bursts which make use of strange matter can be found in Alcock, Farhi, and Olinto (1986) and Haensel, Paczynski, and Amsterdamski (1990).

The properties of nuclear matter at very high densities can, in principle, be tested by the way neutron stars cool. A recent twist on this kind of analyses was brought by the realization that the usually ignored direct Urca process can actually take place in standard nuclear matter for a class of equations of state (Lattimer, Pethick, Prakash, and Haensel, 1991). This possibility makes the distinction of standard nuclear composition with less standard ones (like meson condensates, baryon condensates, quark matter, and strange matter) less trivial. Olinto has been studying this issue following discussions with other participants of the workshop on "Strangeness in Hadrons and Nuclei" at the Institute for Nuclear Theory in Seattle.

This project has also focused on topics where nuclear physics overlap with cosmology. One of such cases is the study of the origin of primordial magnetic fields due to the dynamics of the quark-hadron phase transition in the early universe, done by Cheng and Olinto. If the quark-hadron phase transition is first order it will go through a long period (compared to the Hubble time then) in which both phases co-exist. This coexistence phase will generate a net vorticity in order to satisfy the entropy constraints within each phase and the net expansion of the Universe. This net vorticity will give rise to currents since charge separation occurs, which will ultimately generate a primordial magnetic field. We are presently investigating the spectrum of eddies that carry the vorticity which ultimately determines the final strength of generated magnetic field. Cheng and Schramm have also been investigating the effects of primordial magnetic fields on Big Bang nucleosynthesis.

Our group has been involved in many aspects of primordial nucleosynthesis. Olinto and collaborators have used the results for inhomogeneous nucleosynthesis calculations in order to constrain inhomogeneities that could arise if the eletroweak phase transition is first order.

Thomas and Schramm have began reevaluating the constraints on the lepton number of the Universe from neutrino degenerate nucleosynthesis. Improved observational data and updated nuclear reaction rates led to significantly tighter constraints than was previously possible. We found that even with improved limits on the abundances of $^2H$ and $^3He$, it is possible to obtain a baryon density comparable with the critical density. This requires, however, a very large lepton number and is difficult to reconcile with current models of particle physics. In addition, it appears that further improvements in abundance measurements will be unlikely to enable a distinction to be made between large-lepton-number models and the standard model.

Fields, Schramm, and Thomas have been investigating the theoretical implications of recent observations of beryllium and boron in Pop II dwarf stars. These elements have been detected at a level of $Be/H \sim 10^{-13}$ and $B/H \sim 10^{-12}$ in stars with $Fe/H$ approaching $10^{-3}$. Both these abundances and their ratio are important clues to understanding the chemical content of the galaxy at the very early times when these stars were formed.

Fields, Schramm, and Thomas have been reexamining standard model nucleosynthesis with regard to the production of Be and B. Calculations until recently have emphasized the reaction chain for products up to mass 7, as these were the only elements produced in sufficient quantities to be detected. Recently a number of observers have reported measurable abundances of Be in certain metal poor stars, and in the case of one star the abundance of B has been determined. The figures obtained are several orders of magnitude above what was predicted by standard model calculations. We have updated the nuclear reaction network, introducing more than fifty new reactions, and bringing around twenty up to date. We have also taken into account the uncertainties in certain key reactions. Doing so has shown that standard model abundances of these elements are higher than previously thought, though still below the observations by at least two orders of magnitude. Hopefully this work will provide the impetus to improve measurements of those reaction rates which give the greatest contribution to the uncertainty in the results.

The question now arises, whether or not it is time to abandon the standard model of primordial nucleosynthesis, and turn to a more complex model. The obvious candidate here is nucleosynthesis based on density inhomogeneities. We are currently investigating the effects of our updated network on the inhomogeneous calculation, in order to determine whether or not this model can produce the quantities of Be and B observed recently. An approximate calculation (carried out by artificially raising the neutron to proton ratio in the inhomogeneous model) shows however, that while the inhomogeneous model can produce more Be and B under certain conditions, it is unlikely to explain the abundances observed. It is possible that the Be and B observed is due to cosmic ray spallation. However the important quantity here is the B/Be ratio, and there are currently very few measurements of the primordial abundance of B to make a definite statement. We will be able to make a more precise determination of the abundances of Be and B in the inhomogeneous model. Further measurements of B abundances and of nuclear reaction rates may ultimately allow us to discard either the homogenous or the inhomogeneous models.

Another possible mechanism for producing the recently observed Be and B is cosmic ray spallation in the early galaxy. Indeed, Walker et al. (1992) have pointed out that the Be and B measured so far have abundances that increase with the oxigen abundance, thus pointing to a galactic source for Be and B. We have shown that the observations thus far are indeed consistent with cosmic ray models if one makes the reasonable assumption that the early cosmic ray spectrum was harder than that today. We also pointed out, however, that all cosmic ray models are constrained to produce B/Be ratio of at least 8, so that any detection of Be and B with a ratio much less than 8 would rule out the cosmic ray model for these stars.

Assuming the validity of the cosmic ray model, Fields, Schramm, and Truran have shown (Fields at al 1992) that the Be and B data puts limits on the early cosmic ray flux strength, showing the early cosmic ray output to be enhanced over the current flux, but not by as much as the model for the "bright phase" would suggest. We also show that these data may hint that cosmic ray spallation processes are responsible for an important part of the diffuse gamma ray background.

We are continuing work on cosmic ray spallation models, with a numerical routine to more accurately estimate the cosmic ray production of Li, Be, and

B for different spectra. To do this we are using tabulations of spallation cross sections, as well as information on stopping powers, and the energy-dependent cosmic ray escape ranges. We plan to integrate our code with a full galactic chemical evolution.

Shi and Schramm (1991) worked on the implications of the solar neutrino problem. In particular, they considered full three-neutrino MSW mixing and calculated the corresponding mixing parameter space allowed by both the $^{37}Cl$ and the Kamiokande II experiments. The expected depletion for the $^{71}Ga$ experiment was also calculated. They explored the range of theoretical uncertainty due to possible astrophysical effects by varying the $^{8}B$ neutrino flux and redoing the MSW mixing calculation.

We have found that the constraint from Kamiokande II's limit on the day-night variation is significantly weakened by the mixing with the third family but it is not sensitive to astrophysical uncertainties. The result from SAGE doesn't rule out any significant region of the parameter space in both two and three-family mixing case. The result from GALLEX admits solutions on the upper diagonal region and the vertical region of the MSW parameter space. Overall, our results show the robustness of the MSW solution parameters in the light of astrophysical uncertainties. The current MSW solution gives a mass square difference of $10^{-6}eV^2$. If we assume negligible $\nu_e$ mass and that it mixes with $\nu_\mu$, the mass of $\nu_\mu$ would be around $10^{-3}eV$. According to the see-saw mechanism, a $\nu_\tau$ mass of $\sim 10eV$ is expected, which is extremely interesting in cosmology.

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**Invited Talks at Conferences**

- "Cosmological Nucleosynthesis: Predictions and Tests", D.N. Schramm, International School of Astroparticle Physics, January 6-11, 1991, The Woodlands, Texas.
- "Physical Cosmology,", Second Winter School of Physics, University of Puerto Rico, San Juan, March 27- April 5, 1991.

- "Probing Creation: Testing the Big Bang", D.N. Schramm, Symposium Banquet, IEEE 1991 Particle Accelerator Conference, May 6-9, San Francisco, California.
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