NUCLEAR PHYSICS AND ASTROPHYSICS

Progress Report

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ABSTRACT

We report on recent progress of our research at the interface of nuclear physics and astrophysics. During the past year, we continued to work on Big Bang and stellar nucleosynthesis, the solar neutrino problem, the equation of state for dense matter, the quark-hadron phase transition, and the origin of gamma-ray bursts; and began studying the consequences of nuclear reaction rates in the presence of strong magnetic fields. We have shown that the primordial production of B and Be cannot explain recent detections of these elements in halo stars and have looked at spallation as the likely source of these elements. By looking at nucleosynthesis with inhomogeneous initial conditions, we concluded that the Universe must have been very smooth before nucleosynthesis. We have also constrained neutrino oscillations and primordial magnetic fields by Big Bang nucleosynthesis. On the solar neutrino problem, we have analysed the implications of the SAGE and GALLEX experiments. We also showed that the presence of dibaryons in neutron stars depends weakly on uncertainties of nuclear equations of state. We have started to investigate the consequences of strong magnetic fields on nuclear reactions and implications for neutron star cooling and supernova nucleosynthesis.

DESCRIPTION OF RESEARCH PROGRESS

We summarize below the research at the interface of nuclear physics and astrophysics done by D. N. Schramm (P.I.), A. V. Olinto (Co-P.I.), D. Thomas (research associate), B. Field and X. Shi (graduate students), at the University of Chicago, and B. Cheng at the University of Illinois.

Nucleosynthesis

A. Primordial Nucleosynthesis of B and Be

Recent measurements of elements in population II stars have shown the presence of some previously unobserved light isotopes (${}^6\text{Li}$, Be, and B). While these elements have been observed in population I stars for some time, this is the first time they have been found in the old halo stars believed to be indicative of the early-galactic (and hence possibly primordial) abundances. We addressed the question of whether the observed abundances are due to primordial nucleosynthesis or some other process in the early galaxy. If the source is primordial, these abundances can, in principle, help us to determine the possible scale of inhomogeneities at the nucleosynthesis epoch, and hence provide us with information on the nature of the quark-hadron phase transition.

While it had long been assumed that the production of ${}^6\text{Li}$, Be, and B from primordial nucleosynthesis was negligible, Boyd and Kajino have pointed out that production of these relatively heavy elements is strongly dependent on the size and accuracy of the nuclear reaction network used, and may be significantly higher in inhomogeneous models. Fields, Schramm, and Thomas, together with K.A. Olive, have reevaluated the yields from big bang nucleosynthesis, using a much expanded network. We concluded that while using this expanded network increases the abundances of ${}^6\text{Li}$, Be, and B, the yields are still lower than the observations by two or three orders of magnitude. However, we showed that much of the "flow" through the network is along the neutron-rich side, thus allowing for significantly higher yields from models in which the universe is assumed to have density inhomogeneities at the start of the nucleosynthesis epoch.

B. Inhomogeneous Nucleosynthesis

Inhomogeneous nucleosynthesis is inspired by the hypothesis that some process prior to the nucleosynthesis epoch leaves inhomogeneities in the baryon density. For example, studies of hypothetical first order quark-hadron phase transitions indicate that baryon number inhomogeneities may lead to neutron diffusion through the phase boundary which can result in variations in the neutron-to-proton ratio at the epoch of nucleosynthesis. The earliest calculations of the effect on nucleosynthesis assumed that the neutrons diffused to a homogeneous density before nucleosynthesis began (i.e., that it was only the protons which remained inhomogeneous) and that diffusion effects were negligible during nucleosynthesis itself. Further studies, however, have shown that diffusion of both neutrons and protons during nucleosynthesis have a dramatic effect on the results. In order to produce realistic conclusions, then, it is necessary to divide space into a number of zones, calculating the evolution of elements within each zone and accounting for diffusion of neutrons and protons between zones. With G.J. Mathews and B.S. Meyer, we have been looking at the production of ${}^6\text{Li}$, Be, and B in these models.

C. Constraints on Early Universe Inhomogeneities

Preliminary results from our study of inhomogeneous nucleosynthesis have shown that the baryon number density in the early universe should have been quite smoothly distributed in space; otherwise BBN would not agree with observations of light element abundances. Constraints on the degree of homogeneity are being developed by Copi, in collaboration with Schramm and K. Olive. Olinto and collaborators have been studying the implications of such constraints for phase transitions that occurred before BBN such as the electroweak and the QCD transitions.

D. Be and B from Cosmic Ray Spallation

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 oxygen 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. We also pointed out, however, that all cosmic ray models are constrained to produce a 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 et al 1992) that the Be and B data puts limits on the early cosmic ray flux strength. We showed that the early cosmic ray output may be enhanced over the current flux, but not by as much as some models which invoke an early "bright phase." We also found that the data may hint that cosmic ray spallation processes are responsible for an important part of the diffuse gamma ray background.

We continue to 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 cosmic ray 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. We have also developed new semi-empirical techniques for estimating unmeasured spallation cross sections.

E. Constraints on Magnetic Fields

Cheng, Schramm, and Truran (1993) have calculated nuclear reaction rates in the presence of magnetic fields. We have been using this calculation to constrain the strength of primordial fields by BBN. Preliminary results show that a tighter constraint than previous ones will be obtained. We are exploring the implication of this constraint for models which generate magnetic fields primordially.

F. Constraints on Neutrino Oscillations

Shi, Schramm, and Fields (1993) have studied in detail the effects of neutrino oscillations (both between active-sterile and active-active neutrinos) on Big Bang nucleosynthesis. We have calculated the constraints on the mixings between active and sterile neutrinos from the present observations of the primordial helium abundance and discussed the potential implications on various astrophysical and cosmological problems which involve neutrino oscillations. In particular, we have shown that the large-angle sterile neutrino mixing seems to be excluded as a MSW solution to the solar neutrino problem as well as a solution to the atmospheric neutrino mixing presumably seen in some underground experiments. From our recent analyses using this additional constraint, we expect the next generation of solar neutrino

experiments to be able to resolve the nature of the solar neutrino problem. We also find that sterile neutrinos remain a viable dark matter candidate.

G. Hoyle's Non-Standard Nucleosynthesis

Recently, Fred Hoyle and collaborators have attempted to resurrect a quasi-steady state model of cosmology and have proposed that it may also explain the current state of the Universe. Brian Fields and Craig J Copi have been studying the new steady state model in detail. Their particular focus has been on how this steady state model handles nucleosynthesis. Their work has shown that the steady state model requires numerous ad hoc assumptions and still does not fit the observed light element abundances as accurately as the standard Big Bang model. In particular, the standard Big Bang model predicts the abundances of the light elements in very good agreement with the observed values using only one free parameter, the density of baryonic matter.

The Equation of State for High Density Matter:

The equation of state (EOS) for matter above nuclear densities is starting to be probed both by laboratory experiments and satellite observations in complementary ways. Laboratory searches for evidence and properties of the quark-gluon plasma probe the high entropy range of the quark-hadron transition, while neutron star observations may potentially probe the high-density (lower temperature) part of the phase space. Together with a clearer understanding of the consequences of the primordial quark-hadron transition, these different approaches will complement each other in leading to a deeper knowledge of matter at high energies and densities.

In particular, Brookhaven National Laboratory and CERN have started a series of experiments (at BNL: E814, E858, E878, E864, E911; and at CERN: NA-38, P259) aimed at constraining the properties of dihyperons (like the H-particle) and the search for strangelets (unstable states of strange matter with small baryon number). Results from these experiments will naturally be of great interest to some of our research efforts.

A. Dibaryons:

Encouraged by the recently proposed and ongoing experimental searches for different forms of nuclear states, Olinto and collaborators have been investigating 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, thereby accelerating the cooling of neutron stars. The parameters of dibaryon states can be constrained by requiring that they do not destabilize a 1.4 solar mass neutron star. More recently, we have explored the range of uncertainties generated by different nuclear equations of state and confirmed our previous conclusions (Olinto, Haensel, and Frieman, 1993).

B. Strange Matter

On the subject of strange matter, we have been studying the likelihood of metastable strangelets being formed at temperatures below the transition to a quark-gluon plasma, and whether such droplets could survive long enough to reach a detector. The problem of strangelet longevity and the interactions of strange matter lumps also has

an interesting astrophysical implication, namely, the efficiency of the conversion of neutron stars to strange stars. Friedman and Caldwell (1991) have claimed to rule out the existence of strange matter based on the likelihood of converting every young neutron star to a strange star via strangelet contamination and by assuming that strange pulsars cannot glitch. They assumed that large chunks of strange matter, which are tidally disrupted when a binary system of two strange stars merges, break down into much smaller strangelets. This makes the contamination of supernova progenitor stars more efficient. Such an argument is strongly dependent on the integrity of strangelets; for contamination to be efficient, large lumps of strange matter need to dissociate into strangelets that should then survive in the interstellar (and even intergalactic) medium. If the tidally disrupted chunks are not dissociated efficiently or the smaller strangelets decay in flight, strange stars and young neutron stars can coexist.

C. Origin of Gamma-ray Bursts

A very interesting puzzle in high energy astrophysics today is the origin of gamma-ray bursts. R. Epstein (LANL) and Olinto are working on a non-standard model for the origin of the puzzling gamma-ray bursts which may explain the very sought after spectrum of the bursts. In this model, a very energetic event happens in the neighborhood of an active galactic nucleus (AGN) giving rise to Compton reflection of the AGN spectrum by a highly relativistic plasma ($\gamma \approx 10^3$). 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 at 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).

D. Cooling of Neutron Stars

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 observational distinction between standard nuclear composition and less standard ones (such as meson condensates, baryon condensates, quark matter, and strange matter) less trivial.

Recent ROSAT data together with future ASTRO-D observations should help settle the issue on neutron star cooling. We propose to include the effects of strong magnetic fields on cooling calculations for different reactions and compositions. B. Cheng and collaborators have calculated nuclear reaction rates in the presence of magnetic fields (Cheng, Schramm, and Truran 1993) and will be looking at the implications for neutron star cooling together with Olinto and Truran.

E. Constraints on Dirac Neutrinos from SN1987A

Schramm and collaborators (Mayle et al. 1993) have looked at the constraints on Dirac neutrinos from SN1987A. Spin-flip interactions lead to the copious emission of sterile right-handed neutrinos and cool the core faster than the observed neutrino emission time if neutrinos have Dirac masses exceeding about 3keV. We considered the effects of the equation of state (in particular, pion condensation) on the mass limits. We intend to investigate the role of other possible equations of state (for example, quark matter, strange matter, and baryonic condensates) in changing the constraints on Dirac neutrino masses.

F. Constraints on Neutrino Mixing from Type II Supernovae

Shi has been looking at the role of electron neutrino-sterile neutrino oscillation in the event of a supernova explosion. A significant mixing may hinder the ability of the supernova to explode. It may also cool the proto-neutron star too quickly with respect to the observed cooling time of several seconds. We plan to constrain the parameter space of ν_e - ν_s mixing using the neutrinos observed from SN1987A.

G. Primordial Quark-Hadron Phase Transition

Cheng and Olinto (1993) proposed a new mechanism for the origin of primordial magnetic fields due to the dynamics of the quark-hadron phase transition in the early universe. If the quark-hadron phase transition is first order, the Universe would have gone through a long period (compared to the Hubble time) in which the quark and hadron phases co-exist. This coexistence phase generates a net vorticity in order to satisfy the entropy constraints within each phase and the net expansion of the Universe. This net vorticity together with charge separation gives rise to currents which 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 the generated magnetic field. As discussed in the previous section, Cheng and Schramm have been investigating the effects of primordial magnetic fields on Big Bang nucleosynthesis.

The Solar Neutrino Problem

Shi and Schramm have been working on the implications of the solar neutrino problem. In Shi and Schramm (1991), we 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. We explored the range of theoretical uncertainty due to possible astrophysical effects by varying the ^8B neutrino flux and redoing the MSW mixing calculation.

More recently, in collaboration with J. Bahcall, we have been looking at the solar neutrino problem in the light of the new SAGE and GALLEX results along with the results from Kamiokande and Homestake experiments, using Bahcall's 1000 Monte Carlo generated solar models. We have continued to explore the whole range of implications and found that the situation is unfortunately still quite ambiguous. The differences between observations and the standard solar theory may still be due to either astrophysical input or new neutrino physics. In particular, the astrophysical solution, which requires a cooler Sun than the standard solar model of Bahcall et al., may still be viable. If there were some unknown systematic effect for the ^{37}Cl experiment, in fact the need for new neutrino physics, MSW or vacuum neutrino mixing, is sensitive to the results of the Homestake experiment. We have been studying the implications for future experiments like SNO, Borexino, Super Kamiokande, and the Iodine experiment and believe that this ambiguity will be resolved.

Nuclear Physics associated with possible Mass Extinctions by Supernova Explosions

Schramm and J. Ellis have re-examined the possibility that a nearby supernova explosion could have caused one or more of the mass extinctions identified by

paleontologists. We discuss the likely rate of such events in the light of the recent identification of Geminga as a supernova remnant less than 100pc away, the discovery of a millisecond pulsar about 150pc away, and observations of SN1987A. The fluxes of gamma radiation and cosmic rays on the Earth are estimated and their effects on the Earth's ozone layer discussed. A supernova explosion of the order of 10 pc away could be expected as often as every few hundred million years and could, through its ionizing radiation, destroy the ozone layer for hundreds of years, letting in potentially lethal solar ultraviolet radiation. In addition to effects on land ecology, this could entail mass destruction of plankton and reef communities, with disastrous consequences for marine life as well. A supernova extinction should be distinguishable from a meteorite impact such as the one that presumably killed the dinosaurs. We are now exploring the possibly induced isotopic anomalies.

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