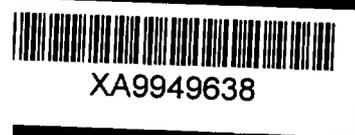the

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THE PHYSICS OF RELIC NEUTRINOS

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United Nations Educational Scientific and Cultural Organization
and
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THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

THE PHYSICS OF RELIC NEUTRINOS

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Abstract

We report on the main results presented at the workshop on The Physics of Relic Neutrinos. The study of relic neutrinos involves a broad spectrum of problems in particle physics, astrophysics and cosmology. Features of baryogenesis and leptogenesis could be imprinted in the properties of the relic neutrino sea. Relic neutrinos played a crucial role in the big bang nucleosynthesis. Being the hot component of the dark matter, they have participated in the structure formation in the universe. Although the direct detection of the sea seems impossible at this stage, there could be various indirect manifestations of these neutrinos which would allow us to study the properties of the sea both in the past and at the present epoch.

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1 Introduction

Neutrinos are one of the most abundant components of the universe. Apart from the 3K black body electromagnetic radiation, the universe is filled with a sea of relic neutrinos which were created in the early stages and decoupled from the rest of the matter within the first few seconds. These relic neutrinos have played a crucial role in primordial nucleosynthesis, structure formation and the evolution of the universe as a whole. They may also contain clues about the mechanism of baryogenesis.

The properties of relic neutrinos, their role in nature and their possible manifestations were the main topics of the workshop on The Physics of Relic Neutrinos. It was organised at The Abdus Salam International Centre for Theoretical Physics (ICTP), Trieste, Italy during September 16 – 19, 1998, by ICTP and INFN.

The workshop was attended by about 80 participants. Around 40 talks were distributed in the following sessions : ● Neutrino Masses and Mixing ● Leptogenesis and Baryogenesis ● Big Bang Nucleosynthesis ● Structure Formation ● Detection and Manifestations of Relic Neutrinos ● Other sources of Neutrino Background ● Neutrinos in Extreme Conditions.

In what follows, we will describe the main results presented in the talks. We also give as complete as possible a list of references to the original papers where the results have been published.

2 Neutrino Masses and Mixing

If neutrinos are massless and there is no significant lepton asymmetry in the universe, the properties of the relic neutrino sea are well known: the neutrinos are uniformly distributed in the universe with a density of 113/cc/species and at a temperature of 1.95K.

The existence of a nonzero neutrino mass can dramatically change the properties of the sea and its role in the evolution of the universe. In this connection, the existing evidences for non-zero neutrino masses and mixing have been extensively discussed.

Recent SuperKamiokande (SK) results on atmospheric neutrinos [1] give the strongest evidence for a nonzero neutrino mass. E. Lisi (Bari) showed that the best fit to the sub-GeV, multi-GeV and upward-going muon data from SK is obtained at [2]

$$\Delta m_{23}^2 = 2.5 \times 10^{-3} \text{ eV}^2 \text{ , } \sin^2 \theta_{23} = 0.63 \text{ and } \sin^2 \theta_{e3} = 0.14 \text{ ,}$$

though taking the CHOOZ results into account will decrease the values of $\sin^2 \theta_{e3}$ and Δm_{23}^2. Maximal depth $\nu_\mu \leftrightarrow \nu_{sterile}$ oscillations can also give a good fit of the data (O. Peres, Valencia), with a slightly higher value of Δm^2 [3].

A majority of alternative explanations of the atmospheric neutrino problem, like a neutrino decay, reviewed by S. Pakvasa (Hawaii), still imply nonzero neutrino masses. The decay of neutrinos can account for the sub-GeV and multi-GeV atmospheric neutrino data rather well [4]. However in this case, the deficit of the upward-going muon fluxes, as indicated by the data from SK and MACRO, cannot be explained.

All the above explanations of the SK results imply that at least one neutrino species has the mass $m \geq 0.03$ eV. This means that at least one of the components of the relic neutrino sea is

non-relativistic, opening up the possibility of the structure formation of the sea.

Though the results on solar neutrinos give a strong hint of the existence of a nonzero neutrino mass, we are still far from the final conclusion. L. Krauss (Case Western) pointed out that if the oscillations are "just-so", certain correlations between the spectral distortions and seasonal variations of the solar neutrino signal may be observable [5].

If both the solar and the atmospheric neutrino anomalies have the oscillation interpretation, neutrinos can contribute significantly to the hot dark matter only if the neutrino mass spectrum is degenerate: all three neutrinos have the mass of about 1 eV. A strong bound on this scenario follows from the negative searches of the neutrinoless double beta decay. With a degenerate mass spectrum, the present bound on the effective Majorana neutrino mass [6] –

$$m_{\text{majorana}} < 0.45 \text{ eV (90\% C.L.)}$$

– implies a large mixing of the electron neutrinos and some cancellation of contributions from different mass eigenstates. Alternatively it means that the neutrino contribution to the energy density in the universe is $\Omega_\nu < 0.06$. F. Simkovic (Comenius) showed that new estimations of the nuclear matrix elements using the pn-RQRPA (proton – neutron relativistic quasiparticle random phase approximation) allow the weakening of the present bound on the Majorana neutrino masses by 50% [7].

The reconstruction of the whole neutrino mass spectrum on the basis of the present data is of a great importance both for particle physics and cosmology. Several plausible patterns of neutrino masses and mixing have been elaborated. One possibility which has attracted significant interest recently (especially in connection with the recent measurements of the recoil electron energy spectrum of the solar neutrinos) is the bi-maximal mixing scheme with degenerate neutrinos [8]. As was described by F. Vissani (DESY), this scheme reproduces $\nu_\mu \leftrightarrow \nu_\tau$ oscillation solution of the atmospheric neutrino problem, explains the solar neutrino data by "just-so" oscillations of ν_e into ν_μ and ν_τ, and gives a significant amount of the HDM without conflicting with the double beta decay bound. However, this scheme requires a strong fine-tuning.

M. Fukugita (Tokyo) reviewed the models of fermion masses based on the $S_{3L} \times S_{3R}$ permutation symmetry which lead to the "democratic" mass matrices for charged fermions. The Majorana character of neutrinos admits a diagonal mass matrix with a small mass splitting due to the symmetry violation. In this case, one gets a large lepton mixing and neutrino mass degeneracy required for HDM. Fukugita presented the embedding of this scheme of mass matrix patterns in SU(5) GUTs [9].

R. Mohapatra (Maryland) showed that the bi-maximal mixing pattern can be derived from the maximal, symmetric, four-neutrino mixing in the limit that one of the neutrinos is made heavy [10]. He also showed that combining the permutation symmetry S_3 with a $Z_4 \times Z_3 \times Z_2$ symmetry in the left-right symmetric extension of the standard model, the mixing pattern of the democratic mass matrix can be generated [11]. This would account for a large $\nu_\mu \leftrightarrow \nu_\tau$ and maximal $\nu_e \leftrightarrow \nu_\mu$ mixing, along with small Majorana masses through the double seesaw mechanism.

The attempts to accomodate all the existing data and / or to explain the large lepton mixing lead to the introduction of sterile neutrinos (Mohapatra) [12]. Their existence would have enormous implications for astrophysics and cosmology. Z. Berezhiani (Ferrara) explored

the possibility of the sterile neutrinos ν' being from a mirror world which communicate with our world only through gravity or through the exchange of some particles of the Planck scale mass [13]. In the mirror world, the scale of the electroweak symmetry breaking can be higher than our scale: $v'_{EW} = z \cdot v_{EW}$, $z > 1$. In this case $\nu_e \leftrightarrow \nu'_e$ mixing can provide the solution of the solar neutrino problem via the MSW effect ($z \sim 30$) or "just-so" oscillations ($z \sim 1$). The mirror neutrinos (and mirror baryons) can also form the dark matter in the universe.

Various aspects of the theory of neutrino oscillations, and in particular the problem of coherence and decoherence in the oscillations, were discussed by L. Stodolsky (MPI, Munich).

3 Leptogenesis and Baryogenesis

In the early universe, one of the first processes directly influenced by the neutrinos would have been those of leptogenesis and baryogenesis. One of the favoured mechanisms for the dynamical generation of the observed baryon asymmetry is through the production of a lepton asymmetry, which can then be converted to the baryon asymmetry by $(B - L)$ conserving electroweak sphalerons [14].

The leptonic asymmetry can be generated in the CP-violating decay of heavy ($M \gtrsim 10^{10}$ GeV) right handed neutrinos N_i to Higgs and usual neutrinos $N_i \rightarrow \ell^c H^*$, $\ell H \rightarrow N_i$. The lifetime of these Majorana neutrinos needs to be long enough, so that the thermal equilibrium is broken. E. Roulet (La Plata) discussed the finite temperature effects on these CP violating asymmetries [15].

E. Akhmedov (ICTP) described a new scenario of baryogenesis via neutrino oscillations [16]. The lepton asymmetry is created in CP-violating oscillations of three right handed neutrino species with masses 20 – 50 GeV. The neutrinos should have very small ($10^{-8} - 10^{-7}$) and different Yukawa couplings. These Yukawa couplings lead both to the production of the RH neutrinos and the propagation of the generated asymmetry to the usual leptons. The lepton asymmetry is generated in different neutrino species, but the total lepton number is still zero. At least one of the singlet neutrino species needs to be in equilibrium and at least one out of equilibrium when the sphalerons freeze out. Then only those neutrinos which are in equilibrium will transform the asymmetry to light ($SU(2)$ doublet) leptons. This asymmetry will be then converted to the baryon asymmetry. Thus, a lepton asymmetry can be produced without a total lepton number violation, through the "separation" of charges.

A. Pilaftsis (MPI, Munich) talked about a model with two singlet neutrinos per fermion family, which get their masses through an off-diagonal Majorana mass term [17]. The mass splitting between these two neutrinos can be small (in E_6 theories, for example) – as small as 10 – 100 eV for the Majorana neutrino masses of 10 TeV. If the splitting is comparable to the decay widths, CP asymmetries in the neutrino decays are resonantly enhanced. A remarkable consequence is that the scale of leptogenesis may be lowered upto the TeV range.

In all the above scenarios, the seesaw mechanism leads to the light neutrino masses in the range $10^{-3} - 1$ eV, which are relevant for cosmology and for explaining the solar and atmospheric neutrino data.

The leptonic asymmetry can also be produced without right handed neutrinos in the decays of two heavy Higgs triplets (U. Sarkar, PRL, Ahmedabad). The Higgs masses of 10^{13} GeV lead

both to a successful leptogenesis and to a few eV scale for masses of the usual neutrinos [18].

In all the above scenarios, the leptonic asymmetry is of the same order as the final baryon asymmetry. In general, a large lepton asymmetry can be produced without a large baryon asymmetry, e.g. through the Affleck-Dine mechanism [19].

In the scenario with the decay of the RH neutrinos, if the hierarchy of the Dirac masses as well as the Majorana masses is similar to that of the up-type quarks, and if the solar neutrino deficit is due to the MSW effect, the temperature for baryogenesis may be as high as $T_B \sim M_R \sim 10^{10}$ GeV. At such high temperatures, however, a large number of gravitinos are generated. These gravitinos might overclose the universe, and if they decay late, modify the primordial light element abundances in a way that is incompatible with observations. According to W. Buchmüller (DESY), these problems can be avoided if gravitinos are the LSPs (and therefore stable), and have the mass 10 – 100 GeV. The relic density of these gravitinos will be cosmologically important and they can play the role of the cold dark matter [20].

4 Big Bang Nucleosynthesis

Properties of the neutrino sea are crucial for the outcome of the big bang nucleosynthesis (BBN), i.e. the primordial abundances of the light nuclides: D, ^{3}He, ^{4}He and ^{7}Li.

The implications of the recent data on the primordial abundances for cosmology and particle physics were reviewed by G. Steigman (Ohio) [21, 22]. The data appear to be in rough agreement with the predictions of the standard cosmological model for three species of light neutrinos and a nucleon-to-photon ratio restricted to a narrow range of

$$\eta \equiv n_B/n_\gamma = (3 - 4) \times 10^{-10}.$$

A closer inspection, however, reveals a tension between the inferred primordial abundances of D and ^{4}He. For deuterium, at present there are two different analyses of the data from the observations of high-redshift, low-metallicity absorbing regions: the first analysis leads to the primordial abundance of [23]

$$D/H = (1.9 \pm 0.5) \times 10^{-4} \ (\text{ high } D),$$

while the second gives [24]

$$D/H = (3.40 \pm 0.25) \times 10^{-5} \ (\text{ low } D).$$

The primordial abundance of ^{4}He is derived from the observations of low-metallicity extragalatic H II regions. Here also, there are two inconsistent results for the ^{4}He mass abundance Y_P. One of the calculations [25] leads to a high number

$$Y_P = 0.244 \pm 0.002 \ (\text{ high } {}^4\text{He}),$$

and another [26] gives a low number,

$$Y_P = 0.234 \pm 0.002 \ (\text{ low } {}^4\text{He}).$$

5

The consistency of the D and ^{4}He results with the predicted abundances in the standard BBN is possible in two cases: (i) low D, high ^{4}He and high η, or (ii) high D, low ^{4}He and low η.

Resolution of this conflict may lie within the statistical uncertainties in the data or with the systematic uncertainties: in the extrapolation from "here and now to there and then". However, if both the D and ^{4}He abundances are low, the Standard BBN is in "crisis". The problem can be resolved if the contribution of some non-standard particle physics leads to an effective number of light neutrino species (N_{eff}^{ν}) at the time of BBN smaller than three. This can be realized, for example, if the mass of the tau neutrino is in the range of a few MeV and it decays invisibly with $\tau \lesssim 5$ sec (S. Pastor, Valencia). In fact, N_{eff}^{ν} can be as low as 1 if the products of the neutrino decay include electron neutrinos, due to their direct influence on the neutron $\leftrightarrow$ proton reactions [27].

A simple statistical method for determining the correlated uncertainties of the light element abundances expected from BBN was presented by F. Villante (Ferrara) [28]. This method, based on the linear error propagation, avoids the need for lengthy Monte Carlo simulations and helps to clarify the role of the different nuclear reactions. The results of a detailed calculation of nucleon weak interactions relevant for the neutron-to-proton ratio at the onset of BBN were presented by G. Mangano (Naples) [29].

The presence of sterile neutrinos in the relic neutrino sea can significantly modify BBN. Though recent conservative bounds on N_{eff}^{ν} still admit more than four neutrino species [30], the question of whether sterile neutrinos can be in equilibrium at the BBN is still alive.

If sterile neutrinos have masses and mixing which give the solution of the atmospheric neutrino anomaly, then the equilibrium concentration of sterile neutrinos will be generated via $\nu_{\mu} \leftrightarrow \nu_s$ oscillations. This can be avoided if the lepton asymmetry of the order $\gtrsim 10^{-5}$ exists at the time of $\nu_{\mu} \leftrightarrow \nu_s$ oscillations [31]. The asymmetry can be produced in the oscillations $\nu_{\tau} \leftrightarrow \nu_s$ and $\bar{\nu}_{\tau} \to \bar{\nu}_s$ at earlier times. The numerical integrations of the corresponding quantum kinetic equations (R. Volkas, Melbourne) show that this requires $m_{\nu_{\tau}} \gtrsim 4$ eV (for $|\delta m_{atm}^2| = 10^{-2.5}$ eV^2) [36]. However X. Shi (San Diego) concludes from his calculations that a ν_{τ} with a larger mass, 15 eV $\lesssim m_{\nu_{\tau}} \lesssim 100$ eV , is neeeded. Such a ν_{τ} must decay non-radiatively with a lifetime $\lesssim 10^3$ years, in order to have a successful structure formation at high redshifts [33]. Recently Shi's results have been criticized by Foot and Volkas [34], who confirmed their previous lower value of $m_{\nu_{\tau}}$.

Volkas also presented the general principles of the creation of a lepton asymmetry as a generic outcome of active to sterile neutrino oscillations ($\nu_a \to \nu_s$ and $\bar{\nu}_a \to \bar{\nu}_s$, where $a = e, \mu, \tau$) in the early universe as a medium. It can be studied from a simpler, Pauli-Boltzmann approach as well as starting from the exact quantum kinetic equations [32]. If a significant electron-neutrino asymmetry ($\gtrsim 1\%$) is generated, N_{eff}^{ν} can be less than three [35].

D. Kirilova (Sofia) discussed the oscillations of $\nu_a \leftrightarrow \nu_s$ with a small mass difference ($\delta m^2 < 10^{-7}$ eV^2). These oscillations become effective after the decoupling of active neutrinos. Using an exact kinetic approach, it is possible to study the evolution of the neutrino number density for each momentum mode. This approach allows one to calculate all the effects of neutrino oscillations on the production of primordial ^{4}He: the depletion of the neutrino population, the distortion of the energy spectrum and the generation of a neutrino asymmetry [37].

5 Structure Formation

Neutrinos are a major component of the hot dark matter (HDM) – the particles which were relativistic at $t \sim 1$ year, when $T \lesssim$ keV and the "galaxies" came within the horizon. The neutrinos with masses in the eV range would contribute significantly to the matter density in the universe:

$$\Omega_\nu = 0.01 \ h^{-2} \left(\frac{m_\nu}{\text{eV}} \right) \ ,$$

and even smaller masses can be relevant for the structure formation. For $\Omega_\nu \geq 0.1$, neutrinos would significantly influence the observable spectrum of density perturbations, giving more strength to supercluster scales and suppressing smaller scales.

The primordial density fluctuations in the universe are probed, in particular, by the anisotropies in the cosmic microwave background (CMB) radiation (for scales $\gtrsim 100$ Mpc), and observations of the large scale distribution of galaxies. Optical red shift surveys of galaxies can now examine scales upto ~ 100 Mpc. As described by J. Silk (Berkeley), no current model seems to fit the detailed shape of the power spectrum of the primordial density perturbations and satisfy all the existing constraints, although the Cold + Hot dark matter (CHDM) model with

$$\Omega_{cold} \sim 0.7, \quad \Omega_\nu \sim 0.2, \quad \Omega_b \sim 0.1$$

gives a relatively better fit [38]. This model implies a neutrino mass (or the sum of the neutrino masses) of about 5 eV and describes the nearby universe well, however it (like the other models with $\Omega = 1$ and zero cosmological constant Λ) is disfavoured by the new data on (i) the early galaxies, (ii) cluster evolution, and (iii) high redshift type IA supernovae.

The models with a cosmological constant, ΛCDM ($\Omega_\Lambda \approx 0.6$), seems to be favoured in the light of the new data [39], but the overall fit is still not satisfactory.

The sizes of voids give an important clue for the relative fraction of the HDM. J. Primack (UC Santa Cruz) described the use of the void probability function (VPF) to quantify this distribution [40]. It is found that on intermediate (2 – 8 h^{-1} Mpc) scales, the VPF for the standard CHDM model (with $\Omega_{cold}/\Omega_{hot}/\Omega_{bar} = 0.6/0.3/0.1$) exceeds the observational VPF, indicating that the HDM fraction is lower than what was thought earlier.

T. Kahniashvili (Tbilisi) argued that that consistency with the current data can be achieved for the (COBE-normalized) models only for

$$\Omega_{hot}/\Omega_{matter} \leq 0.2, \quad h = 0.5(0.7), \text{ and } 0.45(0.3) \leq \Omega_{matter} \leq 0.75(0.5)$$

at 1σ level [41], so that $\Omega_\nu < 0.1$.

The presence of a non-zero cosmological constant, though theoretically problematic from the point of view of "naturalness", seems to help in understanding the large scale structure better. In that case, the main conclusion (as emphasized by M. Roos, Helsinki) is that the presence of HDM is no longer necessary (and eV neutrinos are not needed to provide this component), although some amount of HDM is still possible and may be useful for a further tuning.

The situation can be clarified with new precision measurements of the CMB anisotropy by MAP and PLANCK, which will be sensitive to $\Omega_\nu \sim 0.01$ and therefore $m_\nu \gtrsim 0.2$ eV [42]. S. Hannestad (Aarhus) discussed the role of these in constraining neutrino decays and for detecting the imprints of sterile neutrinos [43]. PLANCK will be able to probe the anisotropy to

the multipole $l \lesssim 2500$, so that the number of neutrino species can be determined to a precision of $\Delta N_\nu \sim 0.05$, which is much better than that obtained from the BBN. New galaxy surveys like SDSS will probe neutrino masses as low as 0.1 eV [44].

The CMB anisotropy measurements also allow us to put a limit on the degeneracy of neutrinos. According to S. Sarkar (Oxford), the present CMB data still admits a rather strong degeneracy (the best fit being at $\mu/T = 3.4$ with the spectral index $n = 0.9$), and hence a large lepton asymmetry. The existence of such a large lepton asymmetry can modify the history of the Universe, leading to symmetry non-restoration at high temperature and thus solving the monopole and domain wall problems [45]. The height of the lowest multipole peak in the CMB spectrum increases with the degeneracy of neutrinos. (The difference in heights between the $\mu/T = 1$ and $\mu/T = 0$ cases is about 10%.) So forthcoming precision measurements of the multipole spectrum will be able to restrict the degeneracy.

6 Detection and Manifestations of Relic Neutrinos

The direct detection of relic neutrinos will of course be of a fundamental importance. However it looks practically impossible with the present methods. The situation have been summarized several years ago in the review [46], and some possible schemes have been proposed in [47]. At the same time, it is possible to search for some indirect manifestations of the relic sea even now.

D. Fargion (Rome) [48] and T. Weiler (Vanderbilt) [49] have considered a mechanism involving relic neutrinos that may generate the highest energy cosmic rays detected at the earth (see for example [50]), which have energies above the Greisen-Zatsepin-Kuzmin (GZK) cut-off of $\sim 5 \times 10^{19}$ eV [51]. The process is the annihilation of ultrahigh energy neutrinos on the nonrelativistic neutrinos from the relic sea:

$$\nu_{\text{cosmic}} + \bar{\nu}_{\text{relic}} \rightarrow Z \rightarrow \text{nucleons and photons} \ .$$

For the neutrino mass $m_\nu \sim$ few eV, the energy of cosmic ray neutrinos should be about $E_\nu \gtrsim 10^{21}$ eV. It is assumed that the production rate is greatly enhanced due to a significant clustering of the relic neutrino density in the halo of our galaxy or the galaxy cluster. The secondary nucleons and photons may propagate to the earth without too much energy attenuation and are the primary candidate particles for inducing super-GZK air showers in the earth's atmosphere. A numerical calculation has been done in [52] which indicates that such cascades could contribute more than 10% to the observed cosmic ray flux above 10^{19} eV in the case of eV neutrinos. Recently Waxman [53] has showed that for the annihilation to contribute significantly to the detected cosmic ray-events, a new class of high energy neutrino sources, unrelated to the sources of UHE cosmic rays, needs to be invoked.

The relic sea could also be detected if neutrinos are massive and undergo a radiative decay. This hypothesis was suggested to explain the high ionization of the interstellar hydrogen. Present status of this hypothesis was summarized by D. Sciama (Trieste) [54]. If this heavy (27.4 eV) neutrino is sterile, it will decouple earlier (at $T \geq 200$ MeV) and its contribution to the matter density Ω will be small, thus avoiding any conflict with the structure formation [55]. Direct searches of the expected EM line at $\lambda \sim 900$ Å from this radiative decay are being performed by EURD detector and the results are expected soon. The decaying neutrino cosmology leaves

a particular imprint in the angular power spectrum of temperature fluctuations in the CMB, which will be tested with the forthcoming MAP and PLANCK surveyor missions.

The evolution of the relic neutrino sea, the possibility of clustering, the formation of structures, local concentrations etc. are of great importance both for direct and indirect detections of relic neutrinos. A possible scenario of the structure formation on galactic scales was discussed by N. Bilic (Zagreb): self-gravitating neutrino clouds can show "gravitational phase transitions" in the process of contraction and form neutrino stars, the scale of whose sizes would depend on the neutrino mass [56].

7 Other Sources of Neutrino Background

Apart from the big bang relic neutrinos, the present universe is filled with relic neutrinos from astrophysical sources: past supernovae, supermassive objects and probably, primordial black holes.

The possibilities of the detection of neutrinos from relic and real-time supernovae with existing and new detectors were discussed by D. Cline (UCLA) and K. Sato (Tokyo). Sato has calculated the expected rate of relic supernova neutrinos at the Super-Kamiokande detector. The rate of supernova explosions is derived from a model of galaxy evolution where the effect of the chemical evolution is appropriately taken into account [57]. Monte-Carlo simulations show that the rate is a few events/year in the observable energy range of 15-40 MeV, which is still about two orders of magnitude smaller than the observational limit at Super-Kamiokande. A similar rate is found for the new experiment ICARUS, described by Cline.

A future detection of a supernova neutrino burst by large underground detectors will provide a measurement of neutrino masses and mixing (Cline). New projects of a supernova burst observatory (SNBO/OMNIS) with an operation time of $\gtrsim 20 - 40$ years were described, where neutrinos will be detected through the secondary neutrons emitted by the recoiling nuclei [58].

A new cosmic neutrino source may be provided by Supermassive Objects (SMOs), that may be formed as the final evolutionary stage of dense star clusters (X. Shi, San Diego). Through relativistic instabilities, SMOs will eventually collapse into giant black holes, such as those at the centers of galaxies. A significant fraction of the gravitational binding energy of the collapse of the SMOs may be released by freely escaping neutrinos in a short period of time (~ 1 sec) with an average energy 1-10 MeV. Neutrino bursts from nearby SMO's ($d \leq 750$ Mpc) may be detectable at ICECUBE, a planned 1 km^3 neutrino detector in Antarctica (an expanded version of the current AMANDA) with an expected rate of ~ 0.1 to 1 burst per year [59].

Some contribution to the relic neutrino sea may also come from the evaporation of Primordial Black Holes (PBHs) through Hawking radiation [60]. E. Bugaev (Moscow) showed that the most favorable energy to detect the flux of neutrinos of PBH origin is a few MeV. Comparison of the theoretically expected neutrino flux from PBHs with Super-Kamiokande data sets an upper bound on the contribution of PBHs to the present energy density of the universe ($\Omega_{PBH} \lesssim 10^{-5}$). This, however, is much weaker than the bounds from the γ-background data.

8 Neutrinos in Extreme Conditions

An important aspect of the physics of the relic neutrinos is the propagation and the interactions of neutrinos in the extreme conditions of the very hot and dense plasma, in strong magnetic fields, etc..

R. Horvat (Zagreb) has used the real-time approach of the thermal field theory (TFT) to calculate the finite temperature and finite density radiative corrections to the neutrino effective potential in the CP-symmetric early universe (see also [61]). The $\mathcal{O}(\alpha)$ photon corrections have been shown to be free of infrared and finite mass singularities, so that bare purturbation series is adequate for the calculations.

D. Grasso (Valencia) has calculated the radiative decay rate of neutrinos in a medium using a generalisation of the optical theorem [62]. This is a powerful method to handle dispersive and dissipative properties of the medium. The results are applicable to the neutrino evolution in the early universe where the electron – positron plasma is ultra-relativistic and non-degenerate.

A. Ioannisian (Munich) discussed the Čerenkov radiation process $\nu \to \nu\gamma$ in the presence of a homogeneous strong magnetic field [63]. Apart from inducing an effective neutrino-photon vertex, the magnetic field also modifies the photon dispersion relations. Even for fields as large as $B_{\text{crit}} \equiv m_e^2/e \approx 4 \times 10^{13}$ Gauss (which are encountered around pulsars), the Čerenkov rate is found to be small, which indicates that the magnetosphere of a pulsar is quite transparent to neutrinos.

9 Summary and Outlook

1. The SK atmospheric neutrino results imply that neutrinos are massive and at least one component of the relic sea is non-relativistic. This opens up the possibility of clustering of neutrinos and the formation of structures.

Forthcoming experiments on atmospheric and solar neutrinos, double beta decay, etc. may shed more light on the neutrino mass spectrum, and therefore, on the relevance of neutrinos for cosmology.

The possible discovery of sterile neutrinos (light singlet fermions) that mix with usual neutrinos will have an enormous impact on astrophysics and cosmology.

2. The simple mechanism of the baryon asymmetry generation via leptogenesis seems very plausible. Moreover, in several suggested scenarios, the masses of light neutrinos are expected to be in the range relevant for cosmology.

Further developments in this field would be related to the identification of the mechanism of neutrino mass generation as well as the studies of alternative scenarios of baryogenesis – like the electroweak baryogenesis based on supersymmetry.

3. The neutrino sea has a strong influence on the big bang nucleosynthesis. Here the observational situation is not clear. Conservative bounds admit more than four neutrino species in equilibrium at the time of BBN, so that one light sterile neutrino in equilibrium is possible. On the other hand, if the observations imply a lesser number of effective neutrino species, it can be accounted for by scenarios like neutrino decay or oscillations into sterile components.

The progress would come from further studies of the systematics in the determination of abundances, restrictions on η, and searches for sterile neutrino effects in the laboratory experiments.

4. Recent cosmological data is changing our understanding of the role of neutrinos as the HDM: it seems that the HDM is not necessary, although some amount is allowed and may be useful for a better fit to the data.

Future cosmological observations will give important information about the neutrino masses, the presence of sterile states, neutrino degeneracy, etc..

5. The direct detection of the relic neutrinos is a challenge. However, indirect observations of the neutrino sea are possible via the studies of the cosmic rays of ultrahigh energies, or through the searches for radiative decays of relic neutrinos.

There are deep connections between the physics of relic neutrinos and a variety of fundamental open questions in cosmology, astrophysics and particle physics. Understanding the properties of the relic neutrino sea and its possible detection will be one of the challenges for the physics and astrophysics of the next millenium.

10 Epilogue

This report is an attempt to substitute the "Proceedings", which are, in many cases, a nightmare for the organisers, a waste of time for the speakers and a practically useless showpiece for the readers due to the time delays. Its objectives were

- to give general information about the meeting (format, participants, topics, etc.),

- to review the results and discussions,

- to give, as much as possible, a complete reference list to the original papers of participants in which the results presented during the conference were published. (Indeed, a majority of the results have been published before or within about two months after the meeting.) We also give some information about other appropriate papers, as well as about further related developments during the short time after the conference.

This review has been written (as an experiment) by the organisers of the workshop. Probably a better idea would be to select "reporters" from among the participants in advance, who will review the conference in a short period of time.

References

[1] Y. Fukuda *et. al.*, the SuperKamiokande Collaboration, Phys. Rev. Lett. **81**, 1562 (1998).

[2] G. L. Fogli, E. Lisi, A. Marrone and G. Scioscia, hep-ph/9808205.

[3] M. C. Gonzalez-Garcia, H. Nunokawa, O. L. G. Peres and J. W. F. Valle, hep-ph/9807305.

[4] V. Barger, J. G. Learned, S. Pakvasa and T. J. Weiler, astro-ph/9810121.

[5] S. P. Mikheyev and A. Yu. Smirnov, Phys. Lett. **B429**, 343 (1998); S. L. Glashow, P. J. Kernan and L. M. Krauss, hep-ph/9808470.

[6] Heidelberg - Moscow collaboration, M. Günther *et. al.*, Phys. Rev. **D 55**, 54 (1997); L. Baudis *et. al.*, Phys. Lett. **B 407**, 219 (1997); H. V. Klapdor-Kleingrothaus, hep-ex/9802007.

[7] F. Simkovic, A. Faessler, G. Pantis and J. D. Vergados, Nucl. Phys. Proc. Suppl. **48**, 257 (1996); J. Schwieger, F. Simkovic, A. Faessler and W. A. Kaminski, Phys. Rev. **C57**, 1738 (1998).

[8] F. Vissani, hep-ph/9708483.

[9] M. Fukugita, M. Tanimoto and T. Yanagida, hep-ph/9809554.

[10] R. N. Mohapatra and S. Nussinov, hep-ph/9809415.

[11] R. N. Mohapatra and S. Nussinov, hep-ph/9808301.

[12] Z. G. Berezhiani, R. N. Mohapatra, Phys. Rev. **D52**, 6607 (1995).

[13] Z. G. Berezhiani, Acta Phys. Polon. **B27**, 1503 (1996).

[14] V. A. Rubakov, M. E. Shaposhnikov, Usp. Fiz. Nauk **166**, 493 (1996), Phys. Usp. **39**, 461 (1996).

[15] L. Covi, N. Rius, E. Roulet and F. Vissani, Phys. Rev. **D57**, 93 (1998).

[16] E. Kh. Akhmedov, V. A. Rubakov and A. Yu. Smirnov, Phys. Rev. Lett. **81**, 1359 (1998).

[17] A. Pilaftsis, hep-ph/9810211.

[18] E. Ma and U. Sarkar, Phys. Rev. Lett. **80**, 5716 (1998).

[19] I. Affleck, M. Dine, Nucl. Phys. **B249** 361 (1985); A. Casas, W. Y. Cheng, G. Gelmini, hep-ph/9709289.

[20] M. Bolz, W. Buchmuller and M. Plumacher, hep-ph/9809381.

[21] G. Steigman, to appear in the Proceedings of the Second Oak Ridge Symposium on Atomic & Nuclear Astrophysics (Oak Ridge, December 1997), astro-ph/9803055.

[22] For a recent review see D. N. Schramm and M. S. Turner, Rev. Mod. Phys. **70**, 303 (1998).

[23] C. J. Hogan, astro-ph/9712031; J. K. Webb et al., Nature **388**, 250 (1997).

[24] S. Burles and D. Tytler, Astrophys. J. **499**, 699 (1998); S. Burles and D. Tytler, Astrophys. J. **507**, 732 (1998);

[25] Y. I. Izotov and T. X. Thuan, Astrophys. J. **500**, 188 (1998).

[26] K. A. Olive, E. Skillman, and G. Steigman, Astrophys. J. **490**, 72 (1997).

[27] A. D. Dolgov, S. H. Hansen, S. Pastor, and D. V. Semikoz, hep-ph/9809598.

[28] G. Fiorentini, E. Lisi, S. Sarkar and F.L. Villante, Phys. Rev. **D58**, 063506 (1998).

[29] S. Esposito, G. Mangano, G. Miele, and O. Pisanti, astro-ph/9808196.

[30] K. A. Olive and D. Thomas, hep-ph/9811444; and references therein.

[31] R. Foot and R. R. Volkas, Phys. Rev. Lett. **75**, 4350 (1995).

[32] N.F. Bell, R.R. Volkas, and Y.Y.Y. Wong, hep-ph/9809363.

[33] X. Shi and G. M. Fuller, astro-ph/9810075.

[34] R. Foot and R. R. Volkas, astro-ph/9811067.

[35] N. F. Bell, R. Foot, and R. R. Volkas, Phys. Rev. **D58**, 105010 (1998).

[36] R. Foot, hep-ph/9809315 (to appear in Astropart. Phys.)

[37] D. P. Kirilova and M. V. Chizhov, Nucl. Phys. **B534**, 447 (1998); Phys. Rev. **D58**, 073004 (1998).

[38] E. Gawiser and J. Silk, Science **280**, 1405 (1998) and references therein.

[39] J. Primack and M. A. K. Gross, astro-ph/9810204.

[40] S. Ghigna *et. al.*, Astrophys. J. **437**, L71 (1994).

[41] T. Kahniashvili, B. Novosyadlyj and R. Valdarnini, Helv. Phys. Acta, v.69, p.219 (1996); R. Valdarnini, T. Kahniashvili and B. Novosyadlyj, Astron. Astrophys. v.336, p.11 (1998).

[42] R. E. Lopez, S. Dodelson, A. Heckler and M. S. Turner, astro-ph/9803095.

[43] S. Hannestad, Phys. Lett. **B431**, 363 (1998); S. Hannestad and G. G. Raffelt, astro-ph/9805223.

[44] W. Hu, D. J. Eisenstein and M. Tegmark, Phys. Rev. Lett. **80** 5255 (1998).

[45] B. Bajc, A. Riotto and G. Senjanovic, Phys. Rev. Lett. **81**, 1355 (1998).

[46] P. F. Smith, Santa Monica Astropart. 1990, 311.

[47] C. C. Speake and J. Leon, Class. Quant. Grav. **13**, A207 (1996).

[48] D. Fargion, B. Mele, and A. Salis, preprint astro-ph/9710029.

[49] T. J. Weiler, preprint hep-ph/9710431 (to appear in Astropart. Phys.).

[50] S. Yoshida *et. al*, AGASA Collaboration, Phys. Rev. Lett. **81**, 1163 (1998).

[51] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G. T. Zatsepin and V. A. Kuzmin, JETP Lett. **4**, 178 (1966).

[52] S. Yoshida, G. Sigl, and S. Lee, hep-ph/9808324.

[53] E. Waxman, astro-ph/9804023.

[54] D. W. Sciama, MNRAS **289**, 945 (1997); J.A. Adams, S. Sarkar, and D. W. Sciama, MN-RAS **301**, 210 (1998); D. W. Sciama, astro-ph/9806174; D. W. Sciama, astro-ph/9811172.

[55] R. N. Mohapatra and D. W. Sciama, hep-ph/9811446.

[56] N. Bilic, D. Tsiklauri and R. D. Viollier, Prog. Part. Nucl. Phys. **40**, 17 (1998); N. Bilic and R. D. Viollier, hep-ph/9809563; N. Bilic and R. D. Viollier, astro-ph/9810108.

[57] T. Totani et al., Astrophys. J. **496**, 216 (1998); T. Totani, Y. Yoshii, and K. Sato, Astrophys. J. **483**, L75 (1997).

[58] G. M. Fuller, W. C. Haxton, and G. C. McLaughlin, astro-ph/9809164; P. F. Smith, Astropart. Phys. **8**, 27 (1997); D. B. Cline et al., Phys. Rev. **D50**, 720 (1994).

[59] X. Shi, G. M. Fuller, and F. Halzen, preprint astro-ph/9805242; X. Shi and G. M. Fuller, Astrophys. J. **503**, 307 (1998).

[60] F. Halzen, B. Keszthelyi, and E. Zas, Phys. Rev. **D52**, 3239 (1995); A. M. Green and A. R. Liddle, Phys. Rev. **D56**, 6166 (1997).

[61] R. Horvat, Z. Phys. **C72**, 485 (1996); R. Horvat, Mod. Phys. Lett. **A12**, 2461 (1997); R. Horvat, Phys. Lett. **B409**, 288 (1997).

[62] D. Grasso and V. B. Semikoz, hep-ph/9808390.

[63] A. N. Ioannisian and G. G. Raffelt, Phys. Rev. **D55**, 7038 (1997).