PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 67, No. 4
October 2006
pp. 735–742

Working group report: Astroparticle and neutrino physics

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Abstract. The working group on astroparticle and neutrino physics at WHEPP-9 covered a wide range of topics. The main topics were neutrino physics at INO, neutrino astronomy and recent constraints on dark energy coming from cosmological observations of large scale structure and CMB anisotropy.

Keywords. Matter effects; neutrino oscillations; neutrino mass models; cosmology; cosmic microwave background; dark energy; large-scale structures.

PACS Nos 98.70.Vc; 98.80.-k; 98.80.Es; 98.80.Cq; 98.80.Bp

1. Introduction

Given the conclusive nature of evidence for neutrino oscillations, the emphasis of the field both theoretically and experimentally has shifted to precision measurements of mass and mixing parameters. Much of the discussion in the neutrino subgroup focused on physics related to the Indian Neutrino Observatory (INO). A panel of experts participated in a discussion which highlighted the key issues related to this major upcoming project. They were Takaaki Kajita, Naba Mondal, Brajesh Choudhary, Manfred Lindner, S Uma Sankar, and Raj Gandhi (Moderator). Several subsequent discussions in the working group (WG) centered around the physics issues raised in the plenary INO session.

Recent developments in cosmology have been largely driven by huge improvement in quality, quantity and the scope of cosmological observations. Besides precise determination of various parameters of the 'standard' cosmological model, observations have also established some important basic tenets that underlie current models of cosmology and structure formation in the universe – 'acausally' correlated initial perturbations in a flat, statistically isotropic universe, adiabatic nature of primordial density perturbations. These are consistent with the expectation of the inflation paradigm and the generic prediction of the simplest realization of inflationary scenario in the early universe. The WG-2 had an expert on perturbations from inflation (Subir Sarkar) who covered this topic in detail in a WG session. In the past year, the location of the peaks in cosmic microwave background polarization power spectrum, and baryon oscillation in the matter power spectrum, have established gravitational instability as the mechanism for structure formation from these initial perturbations. The baryon oscillations in the matter power spectrum at a characteristic scale (corresponding to the co-moving size of the acoustic horizon at recombination) also provides a 'standard ruler' at low red-shift. Hence, this observation has allowed cosmologists to put strong observational constraints on models of dark energy component. The WG-2 had experts on dark energy models and CMB anisotropy (Rob Crittenden) and on the large galaxy surveys of large-scale structure in the universe (Ravi Sheth) who provided the background and leads for using these new observations to constraint models.

The discussions have been divided into five broad themes. The following problems were proposed in WHEPP-9 and some of them followed up later.

2. Background infrared radiation from neutrino decay

We studied the hypothesis that the excess infrared background radiation [4,5] observed by the IRTS and COBE-DIRBE satellite experiments is due to the decay of a sterile neutrino of mass 30 eV with a decay lifetime $\tau = 10^{-3} H_0^{-1}$. This scenario fits the observed infrared spectrum, as shown in figure 1. In addition we explain the re-ionization optical depth of $\tau_i = 0.1$ at $z > 10$ which is needed to explain the polarization anisotropy observed by WMAP.

3. Bound on axion-photon couplings from solar X-ray flux

The axion two-photon coupling is of the form

$$L = gaa\tilde{F}F. \tag{1}$$

In the magnetic field of the Sun ($B \simeq 200$ G), the axions from the core of the Sun which have energies of a (1–4) keV can convert to photons of the same energy.

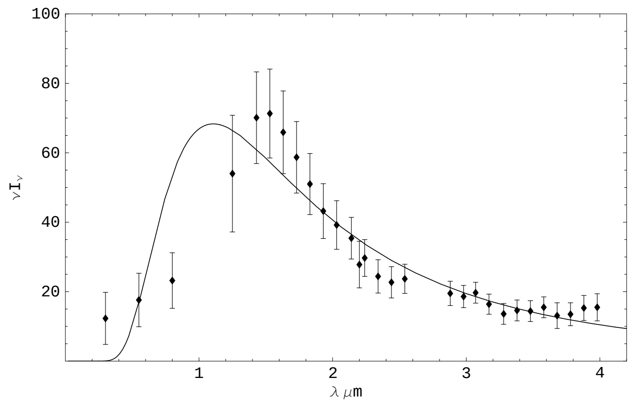

Figure 1. Infrared flux νI_ν in nW/(m^2 str) vs. λ (μm). Data are from IRTS [1], COBE [2] and HST [3]. Theory is particle of mass 30.58 eV decaying radiatively with lifetime $H_0\tau = 1.28 \times 10^{-3}$.

Satellite-based observations of the X-ray flux from the Sun show that the X-ray flux from the Sun in periods with no solar flares is of the order of 10^{-9} W/m^2. It is estimated that a bound on the axion photon coupling of order $g < 10^{-12}$ GeV^{-1} can be put from the solar X-ray data.

4. $\bar{\nu}_e$ from the Sun by RSFP at GADZOOKS

It has been shown [6] that adding $GdCl_3$ to water in the Super-K detector would enhance its efficiency for $\bar{\nu}_e$ observations. It would be sensitive to even the diffused background anti-neutrinos from Supernovae. At WHEPP it was proposed that $\bar{\nu}_e$ which can come from the resonant spin flip (RSFP) of the solar neutrinos in the Sun's magnetic field could also be observed at GADZOOKS. This could improve the existing bounds on the magnetic moment of neutrinos.

5. Observations of radio waves from UHECR impact on the moon

UHECR at energies beyond 10^{20} eV can produce a macroscopic charged current on the surface of the moon [7]. This current will give rise to radio waves as pointed out by Askaryan and observed in terrestrial experiments. A theoretical study of sensitivity of the GMRT telescope to such UHECR-induced radio waves was initiated.

6. $N - \bar{N}$ oscillations

Physics at GUT scale can give rise to $N - \bar{N}$ oscillations with oscillation length of 1 s [8,9]. Big Bang nucleosynthesis is sensitive to the lifetime of the neutron. It is estimated that from nucleosynthesis one can improve the bound on $\bar{N} - N$ oscillations to about 100 s.

7. Neutrino physics at INO

The following talks were given as part of the working group activity in WHEPP-9 for the neutrino physics subgroup and subsequent working group discussions centered around these issues.

1. GLOBES as a tool for neutrino physics – Manfred Lindner
2. Physics reach of the INO-CERN baseline for beta beams – Sanjib Agarwalla
3. Matter effects and mass hierarchy determination in atmospheric neutrinos – Pomita Ghoshal
4. Determining the type of neutrino mass hierarchy in NOvA – Silvia Pascoli
5. Tev scale leptogenesis in L–R symmetric models – Narendra Sahu

8. Physics reach of INO

A discussion of the physics reach of the proposed Indian Neutrino Observatory was conducted. Some of the talks mentioned above summarized the current status of the physics searches and also how it will compare with the other upcoming experiments. A small subgroup consisting of S Agarwalla, P Ghoshal, S Goswami and S Uma Sankar looked into the possibility of determining the hierarchy for $\theta_{13} = 0$. The muon neutrino survival probability in the Earth's matter was calculated for $\theta_{13} = 0$ [10]. The hierarchy difference in matter for this case can be expressed as

$$P_{\mu\mu}^{\rm NH} - P_{\mu\mu}^{\rm IH} = \sin^2 2\theta_{23}\left[\sin^2(1+\alpha c_{12}^2)\Delta - \sin^2(1-\alpha c_{12}^2)\Delta\right], \tag{2}$$

where $\alpha = \Delta_{21}/A$ and $c_{12} = \cos^2\theta_{12}$. The matter potential A is given as $A = 2\sqrt{2}G_{\rm F}N_{\rm e}E$ in terms of Fermi constant, electron density and neutrino energy.

However, it is to be noted that eq. (2) is obtained by taking $P_{\mu\mu}^{\rm NH}$ at $\Delta_{31} = +\Delta_{31}$ while $P_{\mu\mu}^{\rm IH}$ at $\Delta_{31} = -\Delta_{31}$. This situation is applicable when we know the value of $|\Delta_{31}|$ very precisely. However, within the range of uncertainty of $|\Delta_{31}|$ it may be possible to find another close-by value of Δ_{31} for the IH for which the NH–IH difference cease to exist. Let us denote this value for IH by $\Delta_{31} = -\Delta_{31} + x$. Then from the above we get $x = 2\Delta_{21}c_{12}^2$. This value of x renders the muon survival probability for IH and NH indistinguishable. Thus we conclude that if the value of Δ_{31} is not known very precisely then it will be difficult to determine the hierarchy if θ_{13} turns out to be zero. Some ways to solve this problem has also been discussed in [11]. Efforts are now on to see if these can be realized in the context of INO.

9. Primordial perturbations from inflation

Any observational comparison based on the structure formation in the universe necessarily depends on the assumed initial conditions describing the primordial seed perturbations. It is well appreciated that in 'classical' Big Bang model the initial perturbations would have had to be generated 'acausally'. Besides resolving a number of other problems of classical Big Bang, inflation provides a mechanism for generating these apparently 'acausally' correlated primordial perturbations [12].

Besides, the entirely theoretical motivation of the paradigm of inflation, the assumption of Gaussian, random adiabatic scalar perturbations with a nearly scale-invariant power spectrum is arguably also the simplest possible choice for the initial perturbations. What has been truly remarkable is the extent to which recent cosmological observations have been consistent with and, in certain cases, even vindicated the simplest set of assumptions for the initial conditions for the (perturbed) universe.

While the simplest inflationary models predict that the spectral index varies slowly with scale, inflationary models can produce strong scale-dependent fluctuations. The first year WMAP observations provided some motivation for considering these models as the data. Many model-independent searches have also been made to look for features in the CMB power spectrum [13–16]. Accurate measurements of the angular power spectrum over a wide range of multipoles from the WMAP has opened up the possibility to deconvolve the primordial power spectrum for a given set of cosmological parameters [17–21]. Theoretical motivation and models that give features in the power spectrum have also been studied and compared in recent post-WMAP literature [22–25]. Subir Sarkar led a session providing an in-depth understanding of the generation of features in the primordial spectrum from inflation [24].

10. Baryon oscillations in the matter power spectrum and constraints on the dark energy

During the WHEPP-9 workshop, Ravi Sheth and Rob Crittenden discussed recent probes of the dark energy component of the universe. One of the major breakthrough has been the detection of baryon oscillations in the matter power spectrum [26–28].

This not only confirms the well-accepted notion that the large-scale structure in the distribution of matter in the present universe arose due to gravitational instability from the same primordial perturbation seen in the CMB anisotropy at the epoch of recombination but also provides to be a major observational constraint on the model of dark energy.

The acoustic peaks occur because the cosmological perturbations excite acoustic waves in the relativistic plasma of the early universe [31–35]. The recombination of baryons at red-shift $z \approx 1100$ effectively decouples the baryons and photons in the plasma abruptly switching off the wave propagation leaving a characteristic imprint of the sound horizon, which is the co-moving distance that a sound wave could have traveled up to the epoch of recombination. This physical scale is determined by the expansion history of the early universe and the baryon density that determines the speed of acoustic waves in the baryon–photon plasma.

For baryonic density comparable to that expected from Big Bang nucleosynthesis, acoustic oscillations in the baryon–photon plasma is observably imprinted onto the late-time power spectrum of the non-relativistic matter. This is easier understood in a real space description of the response of the CDM and baryon–photon fluid

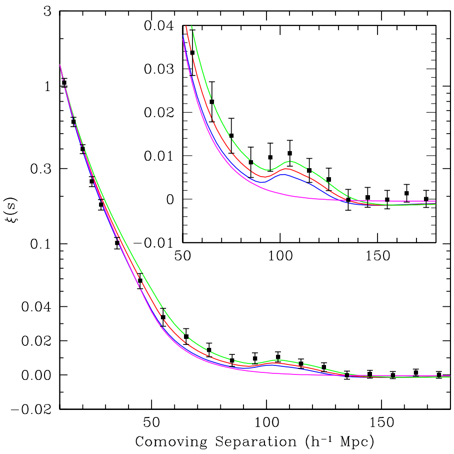

Figure 2. The large-scale red-shift-space correlation function of the SDSS LRG sample taken from ref. [26]. The inset shows an expanded view with a linear vertical axis. The magenta line shows a pure CDM model ($\Omega_m h^2 = 0.105$), which lacks the acoustic peak. The models are $\Omega_m h^2 = 0.12$ (top, green), 0.13 (red), and 0.14 (bottom with peak, blue), all with $\Omega_b h^2 = 0.024$ and $n = 0.98$ and with a mild non-linear prescription folded in. The clearly visible bump at $\sim$100 h^{-1} Mpc scale is statistically significant.

to metric perturbations [26]. An initial small delta-function (sharp spike) adiabatic perturbation ($\delta \ln a|_H$) at a point leads to corresponding spikes in the distribution of cold dark matter (CDM), neutrinos, baryons and radiation (in the 'adiabatic' proportion, $1 + w_i$, of the species). The CDM perturbation grows in place while the baryonic perturbation being strongly coupled to radiation is carried outward in an expanding spherical wave. At recombination, this shell is roughly $105h^{-1}$ Mpc in (co-moving) radius when the propagation of baryons ceases. Afterward, the combined dark matter and baryon perturbation seeds the formation of large-scale structure. The remnants of the acoustic feature in the matter correlations are weak (10% contrast in the power spectrum) and on large scales. The acoustic oscillations of characteristic wave number translates to a bump (a spike softened by gravitational clustering of baryon into the well-developed dark matter over-densities) in the correlation function at $105h^{-1}$ Mpc separation. The large-scale correlation function of a large spectroscopic sample of luminous, red galaxies (LRGs) from the Sloan digital sky survey that covers $\sim$4000 square degrees out to a red-shift of $z \sim 0.5$ with $\sim$50,000 galaxies has allowed a clean detection of the acoustic bump in distribution of matter in the present universe. Figure 2 shows the correlation function derived from SDSS data that clearly shows the acoustic 'bump' feature at a fairly good statistical significance [26].

The acoustic signatures in the large-scale clustering of galaxies provide direct, irrefutable evidence for the theory of gravitational clustering, notably the idea that large-scale fluctuations grow by linear perturbation theory from $z \sim 1000$ to the present due to gravitational instability. We see the same physical scale imprinted as the acoustic oscillations in the CMB angular power spectrum. The ability to measure the same physical scale at the two very disparate red-shifts puts strong constraints on the evolution history of the universe, in particular, $H(z)$, the Hubble parameter as a function of red-shift. In particular, these observations have tightened the scope of deviations of the dark energy from the pure vacuum energy (cosmological constant) in terms of its equation of state, $w \approx -1$.

A few sessions were devoted to the observational probes of dark energy. Special attention was paid to understand the systematics of the baryon oscillation measurement. Ravi Sheth described in detail the measurements of the baryon oscillations. He also touched upon the systematics and limitations coming from, for e.g., the non-linear evolution of the matter power spectrum. A particular model of dark energy in the form of magnetic domain walls proposed by Urjit Yajnik was brought up for discussion [36]. The sessions were designed to bring the awareness of recent cosmological observables, their merits and limitations to the researchers in the HEP who have models for the dark energy component of the universe.

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