Neutrinos from Earth and Heavens

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We present here the session devoted to Neutrinos from Earth and Heavens. It covers in fact three topics : double beta decay, high energy neutrino astronomy and the role of neutrinos in cosmology.

1. Double beta decay

An overview (theoretical and experimental) of the double beta decay physics, which play a key-role in neutrino physics can be found for example in the plenary talk by Klapdor [1]. We just summarize here the challenge of this topic, the present experimental situation and the future projects which have been presented at this workshop.

Double beta decay with emission of two neutrinos ($\beta\beta 2\nu$), though very rare, are allowed processes (conventional second order weak processes). There are 35 potential emitters, on which 10 have been observed (^{48}Ca, ^{76}Ge, ^{82}Se, ^{100}Mo,...), with half-lives going from 10^{19} to 10^{24} years. Double beta decay without emission of neutrinos ($\beta\beta 0\nu$) are allowed only if neutrinos are massive and if they are Majorana particles (i.e. if the neutrino is its own antiparticle). They have not yet been observed and are a powerful probe of particle physics beyond the standard model. The observation of such a process would imply the following relation between the effective mass of the neutrino (a linear combination of the three eigenstates of neutrino masses m_1, m_2, m_3) and the half-life of the process $\mathrm{T}^{0\nu}_{1/2}$:

$$< \mathrm{m}_\nu >^2 = \mathrm{G}^{0\nu}\, |\mathrm{M}^{0\nu}|^2 \,/\, \mathrm{T}^{0\nu}_{1/2} \tag{1}$$

where $\mathrm{M}^{0\nu}$ is the matrix element of the process. The uncertainties in the calculation of the matrix elements have been reduced in the past years, but still need some theoretical work to be fully reliable.

The experimental effort is intense. It consists in identifying a line in the spectrum of the sum of the energy of the two electrons (since no neutrino is leaving, the kinematics of the decay is very simple) ; the requests are then a good energy resolution and a good background rejection. The new generation of experiments uses large sources of enriched materials, and considers different techniques : pure calorimetry (use of germanium crystals), tracking of electrons (use of TPC's) eventually followed by calorimetry (in the NEMO 3 detector), cryogenic detectors (bolometers). The best limit on the $\beta\beta 0\nu$ decay comes from the Heidelberg-Moscow experiment, which uses about 17 kg of germanium enriched in ^{76}Ge in the Gran Sasso Underground Laboratory. The present published result is $\mathrm{T}^{0\nu}_{1/2} > 1.9\,10^{25}$ y [2], inducing a limit of 0.35 eV (90 % c.l.) on $< \mathrm{m}_\nu >$. Several years of running should give a limit of 0.1 eV. The NEMO 3 detector [3] (10 kg of foils of ^{100}Mo but other isotopes are considered) will start in 2001 in Laboratoire Souterrain de Modane and should reach a similar limit, later but with different targets. On the bolometric side, the future could be CUORE (1020 crystals of ^{130}Te), and a 42 kg prototype, CUORICINO, at Gran Sasso, is funded [4].

Two ambitious projects GENIUS and EXO have been presented in our parallel session. GENIUS [5], presented by H.V.Klapdor, consists in 10 tons of germanium crystals (one ton in a first step)shielded by a large amount of liquid nitrogen. EXO [6], presented by G.Gratta, uses the possibility of individually detecting Ba^+ ions in the final state of ^{136}Xe double beta decay via resonant excitation with a set of lasers aimed at a specific location in a large TPC (or several TPC's for a larger detector). They plan to reach a sensitivity as low as 10 meV in 5 years. Will it be sufficient to discover Majorana neutrinos or will it be only an improved limit ?

The challenge of double beta decay without neutrinos is really fundamental with respect to the nature (Dirac or Majorana) for the neutrino, and for the determination of the neutrino mass. One could conclude that time is over in the double beta decay area for too small experiments and that we need one or two large experiments which aim to reach a sensitivity in the meV range. The effort on the theoretical side should also be pursued.

2. High Energy Neutrino Astronomy

Neutrino astronomy is very rich. On an energy scale, if we forget cosmological neutrinos, it starts with solar neutrinos (mean energy of about 1 MeV), continues with supernovae neutrinos [7] (few tens of MeV) and atmospheric neutrinos (values from about 100 MeV to above TeV). Observation of atmospheric neutrinos is not stricto sensu astronomy since these neutrinos come from the interaction of primary cosmic rays with the upper atmosphere ; worse, they constitute a very severe background for high energy neutrinos which could come from astrophysical sources like active galactic nuclei (AGN), gamma-ray bursts (GRB), topological defects or anything else (see figure 1 for an illustration of the variety of the predicted fluxes).

We focus in this section on these high energy neutrinos, just giving some elements to introduce the talks in the corresponding session. The reader is referred to the plenary talk by F.Halzen [8] for a more complete overview.

Detection of high energy gammas has been greatly improved in the last decade either up to the GeV range with the EGRET satellite (hundreds of sources) or up to the TeV range with ground telescopes like Whipple, HEGRA or CAT (few sources but showing dramatic variabilities). With this respect detection of high energy neutrinos is still in the infancy but it is very important for the understanding of the mechanisms which

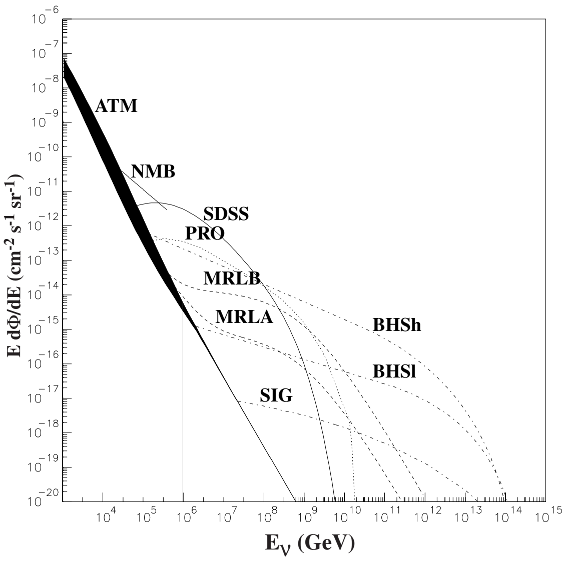

Figure 1. Muon flux predicted by different models for high energy neutrinos. The left thick line (ATM) corresponds to the atmospheric neutrinos. From [9].

govern these astrophysical phenomena to explore also them with neutrinos. The difficulty is that the expected fluxes are small and that very large detectors are needed. Neutrinos (ν_μ) are detected via the muon induced in the interaction (at high energy, the muon keeps the direction of the neutrino with a good accuracy). The detectors must be deployed deeply (to fight against atmospheric muons) under water or under ice and are designed to detect the Cerenkov light emitted by upward-going muons produced by neutrinos having crossed the Earth. They can detect neutrinos above few GeV, but are really optimized above 1 TeV. The basic detection unit is an optical module containing a photomultiplier and each detector will consist of several hundreds (soon) and several thousands (later on) of optical modules.

The different experiments and projects are

Table 1
High energy neutrino astronomy : Experiments and projects.

Experiment	Collaboration		Optical modules	Data taking	Future
Baikal	Russia, Germany	3000 m^2	8 strings 192 PM	Yes	No
AMANDA	USA, Germany, Sweden	$\sim$ 0.01-0.02 km^2	19 strings 680 PM	Yes	Yes ICE Cube
ANTARES	France, Italy, Netherlands, Russia, Spain, UK	R&D "0.1 km^2" funded	13 strings 1000 PM	2002	1 km^3
NEMO	Italy	R&D (site, simulation)			With ANTARES ?
NESTOR	Greece, Russia, Germany	R&D 0.02 km^2	1 tower 168 PM	2001 ?	?

summarized in table 1.

Detection of high energy neutrinos is also interesting with respect to WIMPs which could have been trapped in massive objects like Earth, Sun or the Galactic Center and could annihilate into neutrinos. These WIMPs could have been produced at the big bang epoch and could constitute part of the dark matter. The most promising candidate is the supersymmetric neutralino. Figure 2 shows the rate of muons expected from the Galactic Center in various neutralino models. Several authors have calculated the expected rate of muons coming from the Earth or the Sun as a function of the neutralino mass [11]. Uncertainties are large and the expected signal weak, the advantage being that the background is reduced using the knowledge of the direction of the incoming neutrino. Forthcoming detectors should either to discover the neutralinos or to reject several classes of models.

As quoted for example by E.Waxman [12] observation suggests that gamma-ray bursts (GRB) are produced by the dissipation of the kinetic energy of a relativistic fireball. A significant fraction of GRB energy is expected to be converted to an accompanying burst of high energy neutrinos (in the TeV range). A recent calculation of the experimental signatures of gamma ray bursts in a km^3 neutrino detector has been made in reference [13]. Present models consider a burst of neutrinos in coincidence with the gammas and a less intense burst (called afterglow) on a scale of 10 s. At this Workshop, L.Perrone [14] has presented his model. The numbers he obtains are in reasonable agreement with those previously quoted, i.e. of the order of 10 events per year for a 0.1 km^2 detector.

We now briefly summarize the situation of the different detectors (see table 1 for a list and main characteristics). AMANDA is already data taking at South Pole [15] and the proposal for an IceCube is presently discussed by the NSF authorities. ANTARES [16] has shown the feasibility of the technique in the Mediterranean Sea and is now preparing a 0.1 km^2 detector near Toulon (France) as discussed by Van Dantzig at the Workshop. Located in the North hemisphere, it is complementary of Amanda as it observes in particular the Galactic Center, with some recover for a part of the sky. An Italian Collaboration, NEMO[1], has started R & D on characterization of sites, on detector mechanics and electronics (see the talk by De Marzo [17] at the Workshop). A large part of the NEMO Collaboration has recently joined ANTARES. The Baikal experiment was the first to detect upgoing neutri-

[1]The acronym is the same as the one of the double beta experiment quoted in the first section. The anteriority is in favour of the double beta ... but the link with Jules Verne is more justified for a submarine experiment...

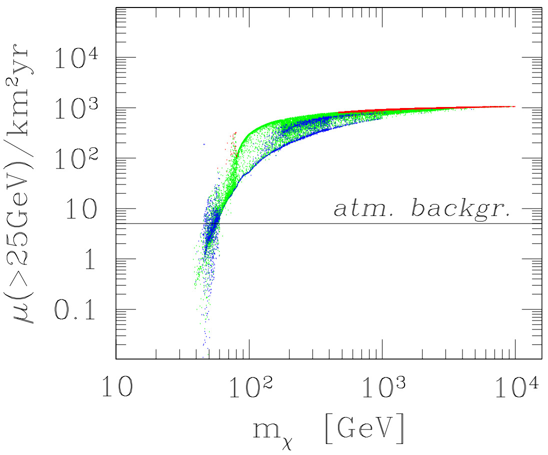

Figure 2. Maximal flux of neutrino-induced muons in a neutrino telescope from neutralino annihilations in the Galactic Center. From [10] .

nos with a limited detector (about 200 modules) with no project for extension. The NESTOR experiment [18] has a technique slightly different : they plan to built floors with several photomultipliers, which is technically more difficult to deploy. They have not yet proved the feasibility of their technique.

We have just mentioned here Cerenkov detectors. They have their limitations and people already think of radio or acoustic detection of neutrinos [19]... but this is a far future.

3. Neutrinos in Cosmology

The interface between neutrino physics on one side and cosmology and astrophysics on the other side has represented one of the most fruitful corners of astroparticle physics. In the past the two major successes of this joint venture were the establishment of the number of 'effective' neutrino species at nucleosynthesis and the upper limit on the sum of light, stable neutrinos from the age of the Universe (by now these are textbook subjects, see for instance [20] for a review).

The other major role played by neutrinos in cosmology was in relation with the Dark Matter (DM) problem. After all neutrinos are the only DM candidates that we know to exist for sure! They constitute the best hot DM (HDM) candidate being very relativistic at the moment they decouple (remember that their decoupling temperature is of order 1 MeV while their masses to be relevant for HDM are in the eV range). There is no problem at all in obtaining a contribution to Ω between 0.1 and 1 for neutrinos of mass around 10 eV. However, it was readily realized that pure HDM could not be suitable to guarantee the growth of the primordial seeds of density fluctuations into the observed large scale structures (galaxies, clusters and superclusters of galaxies). This became quite clear after the results of COBE on the cosmic microwave background radiation (CMB). In any case the failure of HDM as the only source of DM did not represent the end of neutrinos in the DM game. Quite the contrary, it was realized that a convenient admixture of HDM and cold DM (CDM), the so-called mixed DM (MDM) [21], could cure the difficulties of pure CDM models and hence neutrinos were still called to provide a contribution of about 1/3 to Ω.

The ups and downs story of neutrinos as DM candidates has recently known a new and exciting twist with three important classes of observations (for a review, see [22]). First it was realized that the amount of clusterized DM largely failed to provide $\Omega = 1$ (the value $\Omega = 1$, corresponding to a flat Universe, is highly favored by inflation). On the other hand, the position of the first acoustic peak in the angular power spectrum of the CMB anisotropy, as measured by the Boomerang and Maxima experiments , revealed that indeed total Ω is quite close to one. The difference between these two results could be accounted for only if one assumes that there exists a conspicuous amount of so-called "dark energy", i.e. some form of non-clusterized energy density, for instance a vacuum energy leading to a non-vanishing cosmological constant. If this is the case, we should observe its effects in the expansion rate of the Universe. Great was the surprise when the measurement of the "de-acceleration" parameter q_0 from the observation of supernovae used as standard candles revealed that actually the expansion of the Universe was accelerated. This independent evidence of a non-vanishing cosmological constant (or, more generally, of some form of vacuum energy) indeed fitted quite nicely also quantitatively with the previous indirect hint that we mentioned above. This "cosmic coincidence" has led to a new view of the DM problem where now CDM account for something between 0.3 to 0.4 of Ω, with all the remaining 0.7 to 0.6 needed to have $\Omega = 1$ attributed to the "dark energy" [22].

Does all this exclude any possibility for neutrinos to play an active role as DM? First of all it has to be emphasized that as appealing and grandiose all the abovequoted "cosmic coincidence" may appear, we need further confirmation on the data. Moreover, even if they are no longer needed, we cannot say that the presence of some minor contribution of neutrinos to Ω worsens the fit to the power spectrum. In conclusion, HDM in the form of stable, light neutrinos at present is no longer needed, but at the same time it cannot be rejected as a minor component in the contributions leading to $\Omega = 1$.

Curiously enough, if the data of Boomerang and Maxima on Ω contribute to disregard HDM neutrinos, at the same time in particular the height of the second peak could lead to some "rehabilitation" of neutrinos in the cosmological arena. The point is that such peak would indicate a value of the contribution of baryons to Ω which is too large in comparison with the stringent upper bound on Ω_B coming from Big Bang nucleosynthesis (BBN). As we know, BBN with its predictions for light elements abundances ranging over several orders of magnitude and correctly matching the observations represents one of the major triumphs of the standard BB cosmology. One possible wayout to allow for a large value of Ω_B without spoiling the success of BBN is to assume a very large neutrino chemical potential, i.e. the lepton asymmetry $(n_\nu - n_{\bar{\nu}})/n_\gamma$ should be of order 1 instead of being 10^{-9} (we remind that this last value is what one has for the baryon asymmetry) [23].

The presence of a large relic neutrinos asymmetry has several other interesting consequences in addition to the one which we discussed above. It influences the evolution of BBN increasing the expansion rate and affecting the reactions of neutron-proton conversion [24]. It intervenes also in the process of large scale structure formation: the increase in the density of radiation due to the large lepton asymmetry delays the start of matter domination. Finally the relation between the mass of neutrinos and their contribution to Ω is affected: even a neutrino with a mass of 1 eV can provide a contribution to Ωh^2 larger than 0.2 [25].

If a very large relic neutrino asymmetry brings with itself all this host of important consequences, it is relevant to ask: can we really conceive reasonable scenarios where such asymmetry is so enormous to become of order one? The possibility that it originates from oscillations of active and sterile neutrinos in the early Universe has been thoroughly discussed in the literature [26]. The complete treatment of the full quantum kinetic equations is quite complicate; only partially analytic treatments exist, while numerical solutions have been offered [27].

There are several effects deriving from the oscillations of active and sterile neutrinos at BBN. They bring additional particles into equilibrium, they can deplete the number density of electron neutrinos bringing it to values lower than the equilibrium density and, quite important, they can lead to energy spectrum distortion [28]. In particular it is of interest to ascertain the dependence of primordial elements abundances on the parameters characterizing the mixing between the active and sterile neutrino. This has been accomplished [28] with a thorough study of the dependence of the primordially produced helium-4 on the oscillation parameters (δm^2 and oscillation angle) for the full range of mixing parameters with small mass differences ($\delta m^2 < 10^{-7} eV^2$).

In conclusion, if it is true that we are no longer begging neutrinos to contribute to DM to successfully reproduce the power spectrum at very different wavelengths, the interest in the cosmological implications of ligth neutrinos is still quite alive and with new interesting twists. It is clear that neutrinos play a central role in the early Universe physics: BBN, CMB and large scale structure formation are severely affected by their presence and their properties (number of neutrino species, masses, oscillations, etc.). We expect much more (with possible surprises just waiting for us) on the role of cosmological neutrinos from the coming observational cosmology, in particular the MAP, Planck, LSSD,... experiments. The decade in front of us is potentially rich in news of such neutrinos of the distant past.

Acknowledgements

It is a pleasure to thank S.Bilenky, J.Bouchez, C.Carloganu, R. van Dantzig, F.Halzen, and L.Moscoso for discussions and comments. The convivial atmosphere created by G.Fogli and his colleagues at this workshop must be acknowledged.

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