

nomenologists and experimentalists do turn to string theory and its spin-offs in search of a stimulus for ideas on how to detect possible deviations from the standard model. The problems string theory faces are difficult; one approach is to accept this and to plunge time and again into the dark regions of ignorance using string theory as an available guide, hoping that it will be more resourceful than its practitioners are. Another approach is to break away from the comfort of physics as we formulate it today and replace some of its working axioms by new ones, such as holography, the anthropic principle or eventually perhaps something else. It seems that the question of the exact nature of the basic constituents of matter will remain with us for still quite some time. My favorite picture is that it will turn out that asking if the basic constituents are point-like, or are one-, two- or three-dimensional branes, is like asking whether matter is made of earth or air. A theory including the symmetries of gravity will have different phases, some best described by stringy excitations, some by point particles, some by the various branes, and perhaps the most symmetrical phase will be much simpler. Several of these will offer the conventional space-time picture, others will offer something new. String theory, either as a source of inspiration, or as a very dynamic research effort that attracts criticism, leaves few people indifferent.

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About the author

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Particle physics from the Earth and from the sky: Part II

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This second part deals mostly with the results and prospects of non-accelerator physics [1], although several of the themes have a counterpart at accelerators. We will underline recent developments and give a concise report on ongoing projects, their main goals and their present status.

Neutrinos

All reviews of neutrino physics [2] recognize that in this domain the time is truly revolutionary. The proof that neutrinos have non-zero masses has been given by the observation and measurement of oscillations* between neutrino species. This effect provides the differences between masses squared, Δm^2 . Other processes and techniques are needed to measure their absolute values.

Let us recall that Nature is flooding us with huge fluxes of solar electron neutrinos: this amount to $\sim 6 \cdot 10^{10}/\text{cm}^2/\text{s}$, mostly in the 0-0.42 MeV energy range corresponding to the p-p solar process, but with a tiny fraction, in particular from the ^8B process, extending up to 15 MeV. Nature also provides us with atmospheric neutrinos: these are secondaries from cosmic interactions, giving about twice as many muon neutrinos as electron neutrinos, with useful energies between \sim hundred MeV and several GeV. Neutrinos coming from the Earth's radioactivity (roughly equivalent to 10000 GigaW) are about 6 millions /s/cm², but are usually drowned in the flux coming from local reactors. We are immersed in a bath of fossil neutrinos ($\sim 300/\text{cm}^3$), at a temperature of $\sim 1.95^\circ\text{K}$, undetectable directly. Finally we receive neutrinos in the MeV range that originate from Supernova explosions and possible other cosmic sources.

Concerning man-made sources, electron antineutrinos of energies around 4 MeV are produced isotropically from nuclear

* Neutrino oscillations are a quantum mechanical effect. One can identify a particle by the way it is produced or interacts. For instance the positive-pion decay results in a positive muon and a muon neutrino. But one also knows its identity from the knowledge of its mass. Usually these two identifications are the same for each particle. However we already saw in Part I that the quarks are "a bit confused about their identity". For neutrinos the situation is more dramatic: the state that we call for instance muon neutrino is not the same as the particle mass state. The muon neutrino should actually be considered as composed of two states of slightly different masses. These states may be thought of as waves which, for a given energy, have different periodicities and oscillate in and out of phase with each other as they travel along. In one phase the pair interacts as a muon neutrino; but when shifted by 90 degrees it makes a tau neutrino. In between, one would see some fraction of each kind.

One can compare neutrino oscillations to the beats of two neighbouring musical notes. Another analogy would be with the rotation of the plane of polarization of light when passing through some optically active materials. The light is composed of right-hand circular and left-hand circular polarized photons, who travel at slightly different speeds in such media. For neutrinos, however, the oscillations happen even when they travel in empty space.

reactors (a standard nuclear plant produces $5 \cdot 10^{20}$ antineutrinos/s). Accelerators produce directional beams of muon (anti)neutrinos from the decay of focused pions and kaons, with energies between a few hundred MeV and ~ 100 GeV.

In the range of energies considered here the neutrino (antineutrino)-nucleon cross-section is proportional to the neutrino energy and amounts to $0.68 (0.34) \cdot 10^{-38} \text{ cm}^2$ at 1 GeV, a tiny value which explains how demanding is neutrino physics. Neutrinos interact with quarks either by a Neutral Current (i.e. the exchange of a virtual Z^0 , the neutrino keeping its identity) or by a Charged Current (i.e. the exchange of a W, in which case the neutrino is turned into the corresponding charged lepton).

Mass differences and neutrino oscillations

Numerically the oscillation rate goes like $\sin^2 2\theta \sin^2(\pi d/L)$ where θ is the mixing angle ($\theta=45$ degrees corresponds to a full oscillation), d the distance of flight and L the oscillation length which is proportional to $E/\Delta m^2$. The oscillation length for a neutrino energy $E=1 \text{ GeV}$ and a mass squared difference $\Delta m^2=3 \cdot 10^{-3} \text{ eV}^2/c^4$ is about 800 km. From this numerical value it is easy to obtain the oscillation length for any given situation.

The key oscillation neutrino experiments

Starting with the radio-chemical method, the chlorine HOMES-TAKE experiment in the mid sixties, and the gallium GALLEX and SAGE experiments, in which neutrino interactions transform a few atoms of the target into another element, which has then to be extracted, reported a deficit of solar electron neutrinos relative to the expectations of the Standard Solar Model (SSM) [3]. This deficit amounts to 30 to 60%.

The water Cerenkov experiments Kamiokande and especially SuperKamiokande (SK), whose main results appeared in 1998, have measured a deficit of atmospheric ν_μ produced near the antipode of the detector, some 12800 km away, and have shown that the zenith angle dependence of this deficit (i.e. its dependence on the distance d to the source) is well reproduced by an oscillation effect, in which the ν_μ becomes a ν_τ when passing through the Earth. Very recently the first minimum of the oscillation pattern has been observed by SK. Experiments under preparation (OPERA, ICARUS in Gran Sasso, fed by a beam from CERN) will complete the proof by observing directly the ν_τ interaction.

The major results of the last two years [4] are due to:

- the Sudbury Neutrino Observatory (SNO), a 1 kton heavy water experiment in Canada, measuring charged and neutral current events and sensitive to ν_e from the former, and to all active flavours from the latter. SNO demonstrated that the missing solar ν_e have indeed turned into another active species and thus confirmed numerically the validity of the SSM
- K2K, a long baseline oscillation experiment of accelerator-produced ν_μ of 1-2GeV from KEK to SK, 250 km away, that confirmed the atmospheric oscillation observed in SK
- KAMLAND, a terrestrial experiment in Japan, measuring the electron-antineutrino flux from all reactors located within a few hundred km, which confirmed the solar neutrino oscillation and allowed the choice of the so-called Large Mixing Angle solution from competing solutions (figure 1).

Our knowledge of oscillations is thus quite strengthened and several new experiments are underway. The main open question is to know whether there exists a fourth neutrino, of sterile nature, i.e. not coupled to the Z^0 and thus unnoticed at LEP. This was suggested by the LSND experiment at Los Alamos (in which ν_μ from pion decay would turn into ν_e , suggesting a “large” Δm^2 scale of 1eV^2 and very small mixing), but is strongly disfavoured by the other results. The MiniBoone experiment in Fermilab will settle the matter in the coming years.

The results

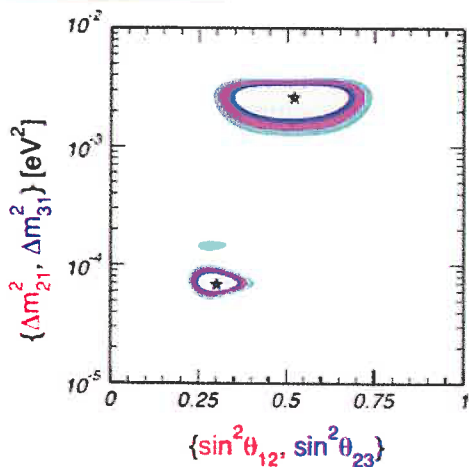
The neutrino mixing matrix, giving the relation between flavour and mass eigenstates, can be written as shown by figure 2 and presents a simple structure in which the various effects are factorized. Figure 1 and 2 give also the numerical value of the measured parameters, the two mass differences and the two mixing angles, which turn out to be maximal in the atmospheric case but not quite so in the solar one.

The big unknown is presently the magnitude of the third mixing angle θ_{13} . Its numerical value will tell whether the ultimate stage of neutrino physics, the measurement of CP violation in this sector, i.e. a difference of behaviour between the left-handed neutrino and the right-handed antineutrino parameterized by the phase δ , is accessible or not. To obtain θ_{13} one needs to measure the $\nu_e \leftrightarrow \nu_\mu$ oscillation. The reactor experiment CHOOZ has set a limit on its value, $\sin \theta_{13} < 0.16$ (90%CL). The next answer will likely come from an oscillation experiment involving a ν_μ beam obtained from an accelerator and a long baseline, as the T2K project in Japan, which could start in 2008, and the US NUMI project. Other possibilities of θ_{13} measurements are also under consideration, such as those involving experimentation close to a nuclear reactor. Further in the future quite ambitious projects could involve very high intensity neutrino beams or “beta-beams” [5] as well as huge new detectors, like a megaton water Cerenkov *à la* SK.

Absolute values of the masses

Oscillations only give access to the mass differences between neutrino mass eigenstates. But one also wants to know their absolute values and to determine the properties of the neutrino mass spectrum. Is it degenerate, i.e. are the three masses close to each other, around some common value, or is it hierarchical, as the spectrum of charged leptons? Is it normal, i.e. with the masses ordered as those of the corresponding charged leptons, or inverted?

To reach the absolute values two different methods are used [6]. The first exploits the β -decay of tritium, through a careful study of the end point of the emitted electron spectrum (the Kurie plot), giving access to the electron neutrino mass m_{ν_e} . The second is a search for neutrinoless double beta decay $0\nu\beta\beta$ (figure 3). In this



▲ Fig. 1: Present status of mass difference measurements and mixing angles from atmospheric (top) and solar (bottom) neutrino oscillations (from M. Maltoni, hep-ph/0401042).

features

process, whose existence is not yet proven, the energies of the two electrons sum up to the energy available in the decay. Its observation, to be possible, requires an extreme level of radiological purity of the detector.

Considering the former method, the upper limit on $m\nu_e$, obtained from the Mainz and Troitsk experiments, is presently 2.2 eV. In future the large KATRIN spectrometer in Karlsruhe should reduce this to 0.2 eV.

The observation of the $0\nu\beta\beta$ process would imply that the neutrino is of the Majorana type. This means that the particle is its own antiparticle, as the graph of figure 3 requires, which is not the case if the neutrino carries a conserved lepton number, opposite for the antineutrino. The NEMO3 experiment, starting in the Frejus underground laboratory, looks for a signal by observing up to 10 kilograms of $0\nu\beta\beta$ decay isotopes (for instance ^{100}Mo , whose signal would be at ~ 3 MeV) and performing an accurate tracking and energy measurement of the two potential electrons. It should in particular settle the open question of a possible signal as claimed by the Heidelberg-Moscow germanium experiment in the Gran Sasso laboratory (the best value of the effective neutrino mass would be 0.39 eV). Later, more ambitious experiments may still gain a good order of magnitude and become sensitive to the neutrino masses, at least in the case of an inverted hierarchy.

Cosmology and neutrinos

Most interesting news concerning neutrinos have been coming from cosmology. Concerning the power spectrum of the Cosmic Microwave Background (CMB) [7], to which we will return later, the presence of relativistic neutrinos tends to suppress the growth of fluctuations at small angular scales. A combination of the results of the satellite programme WMAP (Wilkinson Microwave Anisotropy Probe) and of the galactic survey 2dFGRS (Two degree Field Galaxy General Survey) seems to indicate that the sum of the masses of the three species $\Sigma m\nu_i$ is smaller than 0.71 eV. This limit implies that the heaviest of these masses is in the mass range $0.03 \leq m_3 \leq 0.24$ eV (95% CL). The upper limit corresponds to the degenerate case, the lower one to the lowest bound of the atmospheric mass difference. However several authors call for some caution in extracting such numerical values, given the methodology used and the need to resort to complementary information.

What can we learn from these studies?

What can we expect from the knowledge of the parameters, masses and mixing angles, which govern neutrino physics?

One would like to know whether neutrinos are Dirac or Majorana particles, and from which energy scale their masses originate. Is it from the typical SUSY scale of the order of a TeV? Presently one prefers an origin of the mass linked to a much higher scale, via the so-called “seesaw” mechanism (figure 4), implying the existence

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}}_{\text{atmospheric } \nu \text{ (SK)}} \times \underbrace{\begin{pmatrix} -1 & 0 & e^{-i\alpha_\nu} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\alpha_\nu} \sin\theta_{13} & 0 & -1 \end{pmatrix}}_{\text{reactor and accelerator } \nu \text{ (Chooz)}} \times \underbrace{\begin{pmatrix} 0.85 & 0.51 & 0 \\ -0.51 & 0.85 & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar } \nu + \text{KamLAND (LMA)}}$$

▲ Fig. 2: The factorized neutrino mixing matrix. The atmospheric part reflects the full mixing observed, $\theta=45^\circ$. On the contrary in the solar sector, mixing is large but incomplete. We know from Chooz result that θ_{13} is small. Its actual size will tell whether the phase δ_{CP} is accessible.

at that scale of a heavy right-handed (RH) neutrino, as allowed by Grand Unification. This is another good reason to consider seriously the possibility of Supersymmetric Grand Unification (SGU) that was presented in the first part of this review. This faith clearly calls for a still more sensitive exploration of proton stability. Indeed GU, by unifying leptons and quarks, naturally leads to proton decay, with however a tiny probability of occurrence, given the huge “loan” of energy required to “jump” from 1 to 10^{16} GeV. Some versions of SGU expect that the proton lifetime is within an order of magnitude above the present lower limit ($4.3 \cdot 10^{33}$ years for the mode $e^+\pi^0$, $1.9 \cdot 10^{33}$ years for the mode antineutrino $-K^+$, preferred by SUSY). If giant detectors are conceived for future neutrino experiments, it is imperative as well to consider seriously their ability to detect proton decay.

The results obtained on neutrino properties should guide us in the quest of a theory of flavour. The present experimental results we have discussed already fill a full churchyard of models. But still ignored is whether the neutrino world is an “anarchical” one, in which the parameters have been drawn from a hat at random, or a “hierarchical” one, governed by an underlying law. Knowledge of the value of θ_{13} should contribute to the answer.

A further question is whether that information will tell us something about our “genealogy”, namely matter-antimatter asymmetry, also called baryogenesis [8]? Remarkably, there seems to exist a viable scheme of leptogenesis [9] that finds its origin in the properties and out-of-equilibrium decays of right-handed neutrinos at very high mass scale, and which explains the existing baryon asymmetry, for masses of the usual neutrinos in the range 10^{-3} to 0.1 eV, as observed.

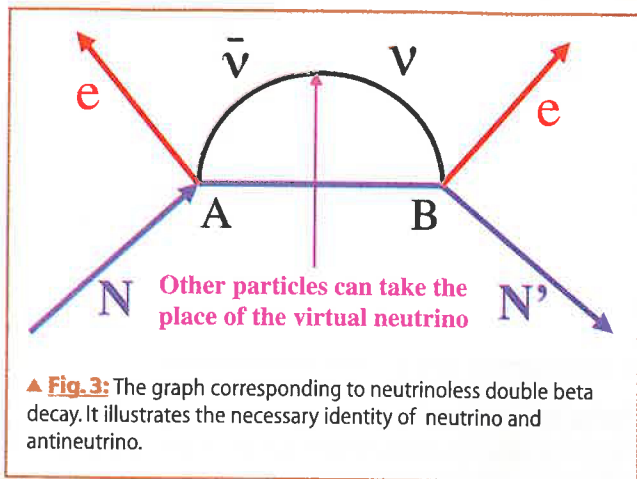
Astroparticle physics

Astroparticle physics is a vast and rapidly expanding domain, concerning now all types of incident particles and whose goal is to obtain information not only on their properties, but even more on the cosmological objects or events from which they originate. We will focus here on the first aspect.

The known cosmic projectiles, except for neutrinos, are bound to interact in the atmosphere. One can thus either detect them directly at very high altitude (balloon or satellite, with a modest detection area, typically 1m^2) or on the ground, through their interaction products. Matter being “transparent” to neutrinos up to huge energies (the Earth becomes opaque above 100 TeV if the cross-section is SM-like), the search for cosmic neutrinos involves gigantic detectors well shielded from ordinary cosmic rays, deep under rock, water or ice.

A still open enigma concerns ultra high energy cosmic rays (UHECR) [10], beyond the Greisen-Kuzmin-Zatsepin (GKZ) cut-off, i.e. particles which seem to have escaped absorption by scattering on the CMB background. Even their existence has to be demonstrated, since the present available experimental results (from Fly’s Eye in Utah and AGASA in Japan) cannot settle the issue. The AUGER programme (with its first site of 3000 km^2 in Argentina), as a result of its two independent and concurrent techniques to detect an atmospheric shower (a fluorescence measurement with telescopes of the Fly’s Eye type, plus an array of ground detectors), should bring the answer and, if they exist, perhaps tell something of their nature.

Gamma Astronomy [11] studies incoming photons, detected either above the atmosphere in balloons and satellites, or on the ground, by large mirrors focusing the Cerenkov light of their shower onto a fine-grained array of photodetectors. Its main objective at present is to fill the gap between low energies (a few GeV, the domain of satellites, EGRET in the past, GLAST in the future) and



▲ Fig. 3: The graph corresponding to neutrinoless double beta decay. It illustrates the necessary identity of neutrino and antineutrino.

high (a few hundred GeV, the threshold of ground detectors up to now). This region can in particular give information about the distribution of the CMB background with which the photons interact. But these detectors are able to tackle several other subjects and search for relic cold dark matter candidates (Weakly Interacting Massive Particles or WIMPs) through their annihilation products, as next discussed. Preliminary results from HESS, a stereo-imaging Cerenkov telescope in Namibia, and the recent start of the 17 meter diameter MAGIC in La Palma (Canarias) are the highlights of the field.

The search for high energy cosmic neutrinos is made either by telescopes measuring both atmospheric fluorescence and Cerenkov light (AUGER, presently in its initial phase, looking at the atmosphere from the ground, EUSO – Extreme Universe Space Observatory, under study for the International Space Station, which would look at a huge volume of atmosphere from far above), or by sub-ice (AMANDA, in operation, ICECUBE, in progress, at the South Pole) and submarine (ANTARES and NESTOR in the Mediterranean sea) Cerenkov experiments. Neutrino astrophysics [12] is certainly a fascinating possibility. Neutrinos, free from absorption, should be able to map the topology of the far Universe in its high energy manifestations. However, given the low probability of interaction of neutrinos, even with km³ sized detectors and in the most favourable conceivable physics scenarios, the rates expected at very high energy are always marginal. No detection of high energy neutrinos (i.e. non solar) of extra-terrestrial origin has been reported so far.

Finally the search for gravitational waves [13] (GW) is also in an exciting phase. Besides studies concerning pulsars which are “natural laboratories” for GW, both the cryogenic bar detectors, operating in coincidence (EXPLORER, AURIGA, NAUTILUS,...) and the large interferometers, presently being commissioned, LIGO, with its two sites in the US, VIRGO, near Pisa, TAMA, in Japan, could open a new method of exploration of the universe. Even further in the future the space interferometer LISA could give access to gravitational waves of much lower frequencies.

Dark matter

Unless one finds a convincing explanation in terms of a deviation from Newton’s law at great distance [14], it is presently admitted that a substantial part of the matter of the Universe is “dark”, i.e. invisible and felt only through its gravitational effect. Moreover most of it must be “cold”, i.e. non-relativistic at the time relevant for galaxy formation. The cold dark matter contribution to the content of the universe has been accurately determined by WMAP to be (29±4%). Concerning its baryonic part (4.4±0.4%, of which only a tenth

corresponds to visible stars), the possibility that it could be mostly due to dark objects like “failed stars” is now excluded. Gas and dust may be the answer.

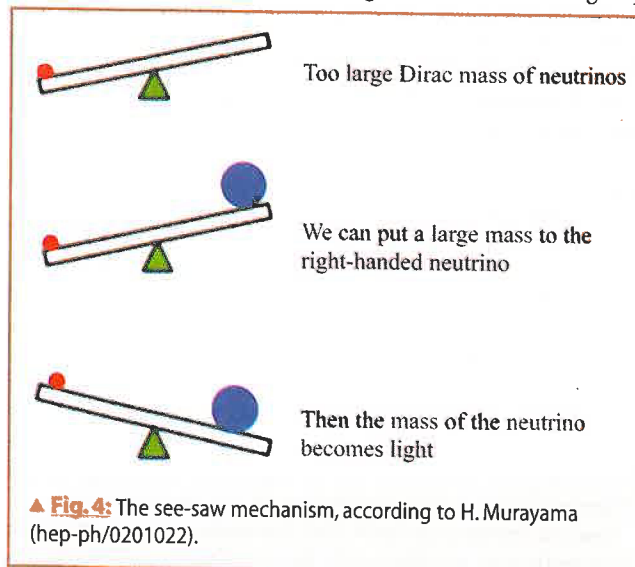
For non baryonic dark matter, for which the search is in full swing, the axion [15] and the neutralino (the highest supersymmetric particle) are still the favoured candidates, although newcomers have appeared, for instance in the frame of theories with extra-dimensions of space.

In the direct search for neutralinos and more generally for WIMPs [16], fossil Weakly Interacting Particles, one looks for the tiny recoil energy that a nucleus struck by the projectile leaves in a detector. This has to be well shielded from cosmic radiation and sensitive to one, or rather several, manifestations of this energy deposit, namely ionization, light or heat.

The DAMA experiment at LNGS (Gran Sasso National Laboratory), exploiting about 100 kg of NaI crystals, continues to give, with more data having been taken, a result that suggests a seasonal variation of its counting rate, for a very low threshold, as could be expected from a halo of fossil neutralinos of about sixty proton masses and the seasonal variation of the Earth’s velocity relative to the halo. An unidentified systematic effect is not excluded and it will be important to obtain independent confirmation of this observation. Neither the Cryogenic Dark Matter Search (CDMS) nor the EDELWEISS experiment in Frejus (which utilize both ionization and phonons as discrimination methods) confirm it, and at first sight they seem to exclude the mass and cross-section regions corresponding to the DAMA effect. However this conclusion has to be considered with caution, given in particular the potential role of spin-dependent interactions of WIMPs with nuclei.

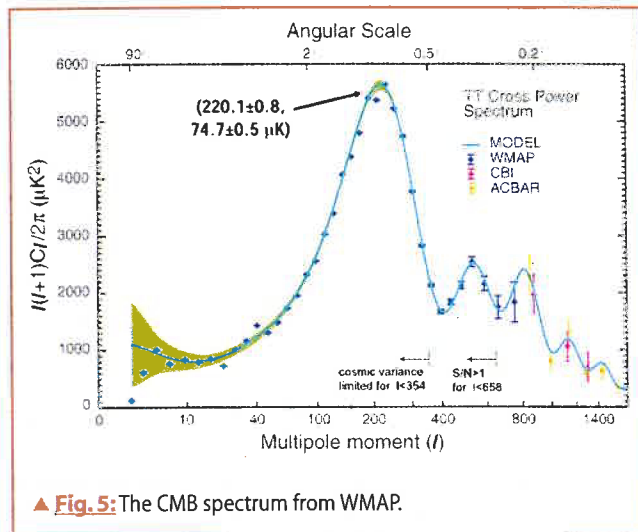
One can hope to gain up to three orders of magnitude in the sensitivity with future experiments. Besides the cross-section of the WIMP-nucleon interaction, one needs assumptions about the local density and the velocity distribution of WIMPs in the halo which is supposed to exist in and around our galaxy. Comparing the expected sensitivities to the predicted values of the cross-section in various SUSY incarnations, the conclusion is that, even if one limits oneself to the rather constrained case of Supergravity (SUGRA), these types of search, although they can bring eventually positive evidence, are unable to falsify the theory in the absence of signal.

A similar conclusion can be drawn concerning the indirect search methods in which one tries to identify an excess of positrons or gamma rays (monochromatic or as a continuum) due to the annihilation of fossils WIMPs, a signal that a Karlsruhe group



▲ Fig. 4: The see-saw mechanism, according to H. Murayama (hep-ph/0201022).

features



▲ Fig. 5: The CMB spectrum from WMAP.

claims to have observed. The players in the game, following after the balloon experiment HEAT and EGRET on the Compton Gamma Ray Observatory satellite, are the satellite-borne spectrometer PAMELA, the Antimatter Spectrometer AMS, which after its initial shuttle flight should be installed on the ISS, the Gamma Astronomy detectors quoted above and, perhaps, the neutrino detectors.

Cosmic Microwave Background Radiation (CMBR)

In the inflation model of the Universe the CMBR spectrum [7] is the result, observed at the decoupling time (namely 380000 years after the Big Bang, the time at which the Universe became transparent to photons) of Gaussian, nearly scale-invariant (an amplitude independent of the wavelength), quantum fluctuations of space-time produced during the inflation period. These fluctuations led to gravitational ones, which induced sound waves in the fluid of electrons, protons and photons. Any region where the density of protons and electrons is higher than average (i.e. a region of compression in a sound wave) is also a region where the density of photons is higher. After decoupling, such a region will appear as hotter than average.

A striking result from the year 2003 is the measurement by the satellite WMAP of the power spectrum of the microwave background (figure 5) with a much better accuracy than previous programmes such as the balloon experiments (ARCHEOPS, BOOMERANG and MAXIMA) and the ground experiment DASI at the South Pole. It covers angular scales extending from ~ 90 degrees (multipole $l \sim 3.5$) to ~ 0.25 degree (multipole ~ 750). WMAP measures also the spectrum of the correlation between polarization and temperature. From the position (in multipole) and the respective heights of the observed peaks and troughs a large number of parameters of the Universe have been extracted with an impressive accuracy. The flatness of the Universe seems to be proven without ambiguity. As for the fraction of dark energy [17] (of matter) Ω_Λ (Ω_m), WMAP alone gives the range 0.5 - 0.8 (0.58 - 0.14) ($\pm 2\sigma$). It also finds most interesting evidence for an early reionization period, probably due to the effect of the first cosmological objects and leading to further rescattering of photons. The only potential anomaly reported could be a lack of power at large angular scale (the smallest multipoles), but in this particular region the so-called cosmic variance (the unavoidable uncertainty due to the fact that we only observe one copy of the Universe) is large and the conclusions are not very significant.

One can therefore say that WMAP has confirmed two of the three major predictions of inflation: the flatness of the universe, linked to

the superluminal, i.e. faster than light, expansion of space, and the existence of density perturbations corresponding to a quasi scale-invariant spectrum (inflation actually predicts a slight deviation from invariance which still needs experimental confirmation). The third prediction, the existence of gravitational waves originating from inflation, is out of reach of the interferometers, even including the futuristic space project LISA. Relevant information can, however, still come from the programmes able to measure the CMBR polarization, in particular DASI, WMAP itself and, later on, PLANCK.

On the other hand the various models of inflation on the market are still rather unconstrained by the present data and the nature of the inflation, i.e. the scalar field whose energy density is supposed to have caused the inflation, stays as a deep mystery.

About the author

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