IL NUOVO CIMENTO Vol. 32 C, N. 3-4 Maggio-Agosto 2009
DOI 10.1393/ncc/i2009-10489-1

Colloquia: IFAE 2009

Neutrino and astroparticle physics

V. Antonelli([1]) and F. S. Cafagna([2])

([1]) *Dipartimento di Fisica, Università di Milano and INFN, Sezione di Milano via Celoria 16, 20133 Milano, Italy*
([2]) *INFN, Sezione di Bari - via Amendola 173, 70126 Bari, Italy*

(ricevuto il 19 Settembre 2009; pubblicato online il 27 Novembre 2009)

Summary. — We report on the neutrinos and astroparticle session of this workshop and discuss the present status and future perspectives of this research field.

PACS 95.85.Ry – Neutrino, muon, pion, and other elementary particles; cosmic rays.
PACS 98.70.Rz – γ-ray sources; γ-ray bursts.
PACS 95.55.Vj – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS 95.55.Ym – Gravitational radiation detectors; mass spectrometers; and other instrumentation and techniques.

1. – Introduction

Summarize a session having such a widespread range of arguments is difficult. Neutrinos and astroparticle physics are argument as waste as the flux and energy ranges of the cosmic rays themselves. In this section we tried to have a paramount view of the arguments, sketching, where it was possible, an ideal line connecting all the contributions.

For sake of simplicity, in this report, we decided to group the two arguments trying to outline the connection.

2. – Present and future of neutrino physics

The structure of the "quasi bi-maximal" PMNS matrix, describing neutrino mixing, is very different from the almost diagonal CKM matrix of the quark case. The PMNS matrix can be decomposed in the product of 3 matrices, each of which has to do with the mixing between a different couple of neutrino mass eigenstates:

$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

where c_{ij}, s_{ij} denote the cosine and sine of the mixing angle θ_{ij} and δ is the Dirac CP-violating phase. The mixing parameters appearing in the first and the last factors of this matrix product can be derived by the atmospheric neutrinos and the accelerator long baseline experiments (for the mixing sector 2-3) and by the analysis of solar neutrino and KamLAND data (for the mixing of the 1st and the 2nd generation). The 1-3 sector of the mixing is, instead, the less known. Up to now we only have an upper limit for θ_{13} ($\sin^2(\theta_{13}) \leq 0.027(0.058)$ at 90% C.L. (3σ)) [1] and one of the main tasks of present and future neutrino physics will be, for sure, to discriminate whether the first and the third neutrino generations are completely decoupled or not and eventually to evaluate the amount of mixing. A zero (or too low) value for θ_{13} would imply the impossibility of measuring CP violation in neutrino physics. For what concerns solar and reactor neutrinos, after the fundamental results of the last years, mainly by SNO and KamLAND, the attention is now focused on the data coming from Borexino, the first real time experiment analyzing the medium energy (below 1 MeV) part of solar neutrino spectrum (mainly the monochromatic ^{7}Be and the pep neutrinos). Borexino will also lower the observation energy threshold for ^{8}B and there is the hope that it can put indirect constraints on the pp and the CNO neutrinos. Borexino data will be important, not only to confirm and corroborate the information about the mass and mixing parameters obtained by previous solar neutrino and KamLAND experiments, but also to improve our knowledge of the Sun properties (like internal temperature and density) and the fusion mechanisms. There is the hope to get at least a partial answer to some questions raised recently, mainly by the measurements of the Sun surface metallicity, which give values significantly lower than before, reducing the agreement between the Solar Standard Model and the measurements of helioseismology. Borexino, more than SNO+ and KamLAND, will be in a leading position also for the geo-neutrinos observation.

Up to now, the most significant results had been obtained by experiments measuring neutrino beams by "natural" sources (solar and atmospheric) and, only recently, by the 1st generation of long baseline accelerator (K2K and MINOS) and reactor (KamLAND) experiments. They were all disappearance experiments and the only claim of appearance, from LSND, has been essentially disproved by the MiniBOONE results. This is mainly due to the fact that the solar neutrino energy scale is well below the kinematical threshold for muon production and, on the other hand, at the atmospheric scale the $\nu_\mu \rightarrow \nu_e$ oscillation is suppressed by the smallness of θ_{13}, while the leading $\nu_\mu \rightarrow \nu_\tau$ oscillation presents the experimental problem of τ identification. A change of paradigm is taking place in neutrino physics. The role played by accelerator and reactor experiments will become more and more central and there is the hope that appearance experiments will be able to confirm and complement the information about neutrino mixing and masses already obtained by the disappearance ones. This new era has been ideally opened by the experiments using the Cern-Gran Sasso beam. The OPERA experiment has been designed with the ambitious aim to discover the signal of ν_τ appearance in a ν_μ beam produced at Cern and delivered at LNGS. The estimates were to get, after five years of nominal beam intensity of 4.5×10^{19} p.o.t. per year, about 10 ν_τ events for a Δm^2 value of $2.5 \times 10^{-3}\,\mathrm{eV}^2$; the number of events would rise to 15 for $\Delta m^2 = 3.0 \times 10^{-3}\,\mathrm{eV}^2$. The expected number of background events is 0.75 and the main background sources are expected to be charm production and decays, hadrons reinteractions and large-angle muon scattering in lead. OPERA successfully operated during the 2008 CNGS run, even if there was an initial partial reduction of the beam intensity (1.78×10^{19}, instead of 2.2×10^{19} p.o.t. in this first run). The analysis of the events collected in the bricks has been very useful to test the efficiency of the system and the background estimates. It has been important, for instance, to prove the possibility of reconstructing events with charm-like decay topologies, very similar to the τ decay ones. The 2009 integrated luminosity is expected to reach 3.6×10^{19} p.o.t. and this should correspond to less than 3

τ events in the 2008-09 data. Another accelerator experiment that is expected to improve significantly our knowledge of the mixing is T2K, that has completed the neutrino beam commissioning and should start the data taking at December 2009. This long baseline is the forerunner of a category of experiments optimized to measure θ_{13}. They will look for ν_e appearance in an intense ν_μ beam, in excess of what expected from the solar terms. In the T2K case the ν_μ originate from a secondary beam produced by the decay of pions obtained by the scattering on fixed target of a high-intensity primary proton beam of 30 GeV at the J-PARC facility. The neutrino beam is studied by an off axis far detector at the SuperKamiokande site (with a baseline of about 295 km), in such a way that the energy peak is tuned at the maximum of oscillation. The sensitivity reached on $\sin^2(2\theta_{13})$ measurement should be of the order of 0.1 already after the first year of data taking. In future years T2K should take advantage of the J-PARC beam intensity upgrading (planned up to 1.6 MW) and by the possible building of Hyper Kamiokande, a water Cerenkov detector with a fiducial volume 25 times bigger than the one of Super Kamiokande. In this way it should be possible to make a significant step forward in the determination of $\sin^2(2\theta_{13})$, reaching a sensitivity well below 0.01 (more than a factor 20 of improvement with respect to the present upper limit from Chooz and almost one order of magnitude lower than the limit that should be reached by OPERA). The T2K experiment is also expected to improve the determination of the atmospheric parameters, with respect to the measurements of Super Kamiokande, K2K and MINOS.

The other possible source of information for θ_{13} determination are the reactor experiments, which are somehow complementary to the accelerator ones. They look for a signal of $\bar{\nu}_e$ disappearance, whose sensitivity, differently from the appearance case studied for accelerator neutrinos, is not influenced by the unknown value of the CP parameter δ. The first results will be obtained by Double Chooz, which anyway should not be able to go beyond the sensitivity of 3×10^{-2} for $\sin^2(2\theta_{13})$ at 90% C.L. In 3-4 years from now other reactor experiments (RENO in South Corea and Daya Bay in China) could become available and they should be able to reach a level of sensitivity competitive with the one of T2K and eventually of the accelerator experiment NOνA. The sensitivity reachable at the first T2K phase and at the future reactor experiments could be not sufficient to determine the value of the mixing between the 1st and the 3rd neutrino generation and, most probably, to measure the eventual leptonic CP violation. The natural extension will be to develop the so-called superbeams. In superbeams, like in the conventional accelerator experiments, the neutrinos under investigation would be produced by a secondary meson beam, but the novelty would be the much higher intensity of the primary proton beam. A first possibility to reach this aim would be to upgrade an already existing facility (like in the case of the second T2K phase). A different alternative would be to build a superbeam that can be considered also as a first step towards a neutrino factory, like in the SPL Cern project.

To make a prediction about the further evolution of accelerator neutrino physics after the superbeam experiments is quite a difficult task. The real need and the discovery potential of new experiments are strongly influenced by the unknown value of of the θ_{13} mixing angle. If it has a value around 3°, a superbeam like T2K (in its second phase of working) should be able to measure it. For lower values (for instance $\theta_{13} \simeq 1^\circ$) a new kind of experiments would be needed. However, if the mixing is too low it could almost be impossible to discriminate if it is zero or not and for a value of θ_{13} significantly lower than 1° there will be essentially no hope to measure the leptonic CP violation phase in terrestrial experiments. In any case, any further improvement with respect to the superbeams would imply a real change in the experimental techniques adopted and in this new kind of facilities the neutrinos under investigation would be produced directly by the decay of a primary beam. There are two different kinds of proposals going to this direction: the beta beams and the neutrino factories. In a beta beam experiment a high-intensity beam of ν_e ($\bar{\nu}_e$) of a few GeV (or even lower energies) would be produced directly by the decay in flight of accelerated radioactive ions. Typical ions usually considered are ^{6}He (for $\bar{\nu_e}$ beams) and ^{18}Ne in the ν_e case. Beta beams present the advantage, with respect to neutrino factories, to have a pure neutrino (or antineutrino) beam, with essentially no contamination of neutrinos of the wrong sign and, moreover, they usually have higher values of the so-called "quality factor" (that is the ratio between the Lorentz factor γ and the center-of-mass energy), proportional to the number of interactions. In the neutrino factory case well-collimated neutrino beams would be originated by the decays of accelerated muons, with characteristic energies of the order of tens of GeV. These facilities would offer the opportunity of studying different channels and, among the others, the two that are usually denoted the golden and the silver channels of appearance. The first one is the search for a $\nu_e \to \nu_\mu$ ($\bar{\nu}_e \to \bar{\nu}_\mu$) transition through the detection of wrong sign muons; in the silver channel case one looks, instead, for a ν_τ appearance, which is a signal of ν_e-ν_τ oscillation. Neutrino factories could offer a very powerful tool to study the mixing in the 1-3 sector, sounding even the region of very low mixing angle values, and look for CP violation, but there is a series of technological caveats to keep in mind in order to realize such a facility, like, for instance, the problems of targetry and muon cooling. An intense *R. D.* project is still going on in this direction [2], with the help also of dedicated experiments like MERIT at CERN and MICE at RAL.

The next years could be crucial not only to complete, or at least improve, the pattern of neutrino mixing, but also to attach some fundamental unresolved questions, like the hierarchy and origin of masses and the real nature of neutrino. A central role should be played by the experiments looking for neutrinoless double-beta decay ($0\nu\beta\beta$), a cristal clear signal of the Majorana nature of neutrino. Two different approaches have been pursued in this field. In some experiments (like NEMO3, that is still running) the radioactive source is distinct from the detector; in other cases, instead, the calorimetric technique is adopted and the detector is built using a material that is also the double-β decay candidate. This solution, adopted for instance by the Heidelberg-Moscow Collaboration and by cryogenic experiments, like Cuoricino and Cuore, puts more constraints in the choice of the possible detectors and sources and can suffer of a difficult topological reconstruction of the event. However, it has a high intrinsic efficiency, with the possibility of using large source masses and a very good energy resolution. Up to now, the most stringent limit for the effective Majorana mass of neutrino, found by the Heidelberg-Moscow Collaboration(^{1}), was: $\langle m_\nu \rangle \leq 0.3$–$0.6\,\text{eV}$. Recently also Cuoricino published its results: $\langle m_\nu \rangle \leq 0.2$–$0.68\,\text{eV}$, where the main source of uncertainty is, as usual, the indetermination on the nuclear matrix elements. Cuoricino is a tower of 13 modules made up by TeO_2, which contains ^{130}Te, an ideal candidate for $0\nu\beta\beta$ decay. The natural expansion of Cuoricino will be the CUORE experiment, an array of 19 Cuoricino-like towers, for a total mass of about 750 kg of TeO_2, that should start working in 2012. A conservative estimate for CUORE is to reach the sensitivity of about 0.05 eV.

One of the most delicate tasks is to pass from this great deal of data to a theoretical model giving a coherent explanation of lepton masses and mixing. For many years

(^{1}) There is also a very controversial claim, from part of the collaboration, of a discovery evidence for $\langle m_\nu \rangle = 0.39\,\text{eV}$.

people used to build models with a vanishing θ_{13} angle and a maximal θ_{23}, in which neutrino matrix exhibits a $\mu - \tau$ symmetry $((m_\nu)_{22} = (m_\nu)_{33}$ and $(m_\nu)_{12} = (m_\nu)_{13})$. To be predictive one needs to introduce some inputs in addition to $\mu - \tau$ symmetry. For instance, imposing the relation $(m_\nu)_{11} = (m_\nu)_{23} + (m_\nu)_{22}$, the mixing matrix assumes the so-called bimaximal pattern and one gets $\sin^2(\theta_{12}) = 1/2$. This class of matrices can fit only partially the data and large corrections, of the order of the quark mixing parameter $\lambda_C \simeq \sqrt{\frac{m_d}{m_s}}$, are needed to account for the experimental value of θ_{12}. An alternative possibility is given by models in which, in addition to the $\mu - \tau$ symmetry, there is the so-called magic symmetry $(m_\nu)_{11} = (m_\nu)_{22} + (m_\nu)_{23} - (m_\nu)_{13}$ and the mixing matrix assumes a form called tri-bimaximal, corresponding to $\sin^2(\theta_{12}^{\mathrm{TB}}) = 1/3$, $\sin^2(\theta_{23}^{\mathrm{TB}}) = 1/2$ and $\sin^2(\theta_{13}^{\mathrm{TB}}) = 0$. Usually in this kind of models the corrections introduced are relatively small (of the order of λ_C^2 or even lower) and they tend to give values of θ_{13} very close to 0. In the last years there was a wide diffusion of models in which the tri-bimaximal pattern was realized assuming different initial symmetries, with discrete and even continuous groups. The recent experimental data and phenomenological analysis, that seem to suggest values of θ_{13} different from zero, caused a revival of the bimaximal pattern, modified with the introduction of order λ_C corrections. This is the case, for instance, of the model described in [3], based on a discrete S_4 symmetry. It reproduces the leptonic mixing with a reactor angle close to its upper limit and the correct mass hierarchy for charged leptons and is also compatible with leptogenesis limits.

Since ever neutrino physics has been strictly connected to astronomy and nowadays time are mature to go back to the original idea of using "neutrino astronomy" as a powerful tool to study the properties of different cosmic sources, like the Sun and other stars and the supernovae. Recent studies [4] analyzed in detail the mechanisms of neutrino (antineutrino) production in the various phases of the core collapse supernovae and the relative detection possibility. They stressed, in particular, the importance, proved by the analysis of SN1987A data, of the 1st phase of rapid accretion, usually neglected in previous studies. For a better comprehension of these phenomena, it would be fundamental to collect data from eventual future galactic supernovae, even if the frequency estimates for such an event are quite discouraging. The study of eventual neutrino signals would be essential also to test the validity of theories predicting the role of supernova remnants (SNR) as cosmic-ray accelerators. Neutrino telescopes could, in principle, detect high-energy neutrino signals coming from different possible SNR in the Milky Way [4].

3. – Present and future of Astroparticle

We are living an exciting era in which multiwavelength measurement campaign will open new prospectives in the study of cosmic-ray sources and acceleration. Data from the radio to the x and VHE γ bands are available and we are waiting for the results of the neutrino telescopes that will extend data beyond the usual electro-magnetic band. At the same time data from ground-based array and satellite-born detectors are constraining model of cosmic-ray sources, acceleration and propagation in different energy ranges. The combination of all these data is rewamping the field producing a great interest in either the phenomenological studies and proposal for new detectors or experiments.

Usually neutrino source candidates are also TeV γ-ray sources, in addition a mechanism like the *astrophysical hadronic model* predicts a strong relationship between the spectral index of the cosmic-rays energy spectrum, and that of γ-rays and neutrinos, featuring an intriguing connection among primary cosmic rays, γ-rays and neutrino astronomy [5]. Having the neutrino astronomy as the principal scientific objective, neutrino telescopes have been built and are running. Among them: IceCube detector at the South Pole and ANTARES deployed in the sea of Toulone, France [6,5]. In the meantime NEMO detector is testing its towers in the sea of Capo Passero, Italy, while the KM3Net Collaboration is preparing a techinical design report for a km^3 scale neutrino telescope to deploy in the Mediterranean Sea [5].

In this view simultaneous observations, like that of the active galactic nuclei (AGN) BL Lac PKS 2155-304 [7], in the optical, X-rays, and γ-rays, up to the TeV region, are an important tool for understanding the nature of the source. In the PKS 2155-304 specific case for the first time an AGN was observed from ground-based telescopes: ATOM (visible) and HESS (UHE γ), and space-borne ones: RXTE (X-rays), SWIT (X-rays) and FERMI (VHE γ). This has been possible thanks to the tremendous improvements of the detectors both space and ground based. Furthermore the enormous potential of FERMI for new discovers and its extremely precise study of γ-ray sources has been shown. In its first months of activities FERMI already discovered several new pulsars and blazars along with new class of pulsars. This will shed new light on the study of the source models and will have consequences not only in the γ astronomy but, in general, in the origin and propagation models as well [7]. In this perspective the ground-based γ-rays telescope will play an important role in exploring the extreme part of the energy range. MAGIC is an experiment of this class which has already proven its capabilities and is going to improve its performances with the important upgrade which led to the MAGIC-II phase. This upgraded detector has been officially opened this year and we are waiting for new data.

The study of the γ sources is deeply related to the problem of the origin and composition of the cosmic rays. The discovery of a VHE γ emission from a molecular cloud containing supernova remnants (SNR) supporting a hadronic origin of this radiation, brings us directly into the *classical* argument of the origin, composition and propagation of the cosmic rays. This is strictly related to the intriguing behavior of the all particle spectra and the explanation of its features, the so-called *knee* and *ankle*, in the energy regions 10^{14}–10^{15} eV and 10^{19}–10^{20} eV, respectively. Big improvements in the ground-based Extensive Air Shower array (EAS) lead to a better knowledge of the composition and spectra in the *knee* region constraining source and propagation models proposed to explain this feature. Results from the EAS favor a scenario in which the *knee* is due to the astrophysical mechanisms such as the acceleration at the source and the propagation. For a better understanding of the models, precision measurements of the *knee* region are needed and next generation EAS detectors, like KASKADE-Grande, are going to fulfill such a request [8].

Catastrophic astrophysical phenomena, like for example a gravitational collapse, will not only produce particles and electromagnetic radiation, but also gravitational waves [4]. For example the study of the $\bar{\nu}_e$ spectra from a galactic supernova will predict the moment of the matter recoil on the neutron star kernel, with high probability associated with a gravitational wave, with a precision of 10 ms [4]. This extends the multiwavelength observation of a source to the gravitational wave antennas. In the last year almost all the antennas adopted the laser interferometer technique. A world network of kilometer-scale laser interferometers has been set-up and is taking data but the sensitivity of the included antennas does not seem enough to give results in a reasonable time. For this reason all the presently working interferometers have planned enhancements in the next few years. Both LIGO and VIRGO, the two larger kilometer-scale interferometers, are already in the design phase of the Advanced-LIGO and Advanced-VIRGO detectors. In the meantime the LISA pathfinder mission, scheduled in 2011, will prove the feasibility of satellite-based constellation of three satellites implementing a laser interferometer in space [9]. It is worth mentioning that the study of massive objects, like a neutron star, is not only important because of the above-mentioned astrophysical characteristic, but also because they could provide a unique windows on the properties of QCD at high baryon densities [10].

Looking back at the all particle spectrum and moving forward to the ultrahigh energy region, the *ankle*, the measurements of AUGER have opened the field of UHE particle astronomy. The quest for UHE point sources is started and there are proposals for detector, with enormous geometrical factor, exploiting the detection of an air shower downward looking the Earth from the space, instead of the more conventional EAS approach of a detection upward looking from the ground. JEM-EUSO is proposing this technique, that, leveraging the field of view of a fluorescence detector looking down the Earth atmosphere, will make it possible to reach a geometrical factor of the order of $10^5\,\mathrm{km}^2\,\mathrm{sr}$ [11].

Any measurements of the cosmic-ray spectra at the *knee* and *ankle* energies, regardless of the experimental technique used, have to heavily rely on simulations. EAS results on composition and energy reconstruction depend on the model used to simulate the interaction of the primary with the atmosphere [8]. Simulations have several systematic errors and uncertainties, including the fact that total cross-sections are not measured yet at these energies. The LHC accelerator offers the unique possibility of measuring cross-sections and comparing interaction models in this energy range. Along with the LHC experiments in the interaction points, there are dedicated experiments to investigate these fields in pseudorapidity regions not covered by the LHC experiments. LHCf is one of these experiments [12]. It is composed of two detectors placed 140 m away from the ATLAS interaction point in the two opposite sides of the LHC tunnel. The two detectors have been installed and built to guarantee redundacy and high background rejection. They are made of common part of tungsten absorbers and scintillator detectors, but differ for the interleaved detectors used to measure the transverse topology and characteristic of the shower. In particular in one side scintillator fibers are used, in the opposite silicon microstrip detectors. The goal is to measure, in a high pseudorapidity range, the spectra of γs, π^0s and neutrons produced in the LHC interaction point and compare them to the prediction of the models used in the EAS data analysis like, for example DPMJET, QGSJET and SIBYLL [12].

Since its discover the search for dark-matter candidates has became an important field of research in the astroparticle physics. Hints for dark-matter candidates can be found in precision studies of primary cosmic-rays spectra, the so-called indirect methods. Direct detection is of course favorable but very sensitive detectors with extremely low background are needed. The DAMA/LIBRA experiment is in operation in the Gran Sasso laboratory. It is an evolution of the DAMA/NaI experiment. Both have collected a total exposure of $0.82\,\mathrm{ton} \times \mathrm{y}$ in about 7 years. DAMA/LIBRA has recently confirmed the model-independent evidence of the presence of dark-matter candidates in the galactic halo studying the annual modulation of the signal [13].

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It is a pleasure to thank the local organizers for giving us this opportunity, all the speakers and audience of the session for interesting contributions and stimulating discussions.

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