Neutrino experiments in Physics Department of Rome ’ Sapienza’ University

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ABSTRACT

This paper will describe the history of experimental neutrino physics in the Physics Department of the Rome 'Sapienza' University.
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1 Introduction

This article will describe the development of neutrino physics in the Physics Department of the 'Sapienza' Rome University.

The ”Istituto Nazionale di Fisica Nucleare” (INFN) supported particle physics activity since its foundation. Members of the Department and of the INFN Section proposed, participated and led the design, construction and data analysis of neutrino experiments.

Particle Physics at the Sapienza began when Fermi and his group moved in the newly built Department in 1936. After the departure of Fermi, due to the racial laws, particle and nuclear physics continued during the difficult years of the war. In these years Marcello Conversi, Ettore Pancini and Oreste Piccioni performed a fundamental experiment on the nature of the hard component of cosmic rays discovering the heavy electron, the muon. The muon was the heavier replica of the electron. There were experiments to study cosmic rays, in the Italian Alps, with balloons flights and in laboratories. In 1975 Marcello Conversi proposed studying charm particles produced by neutrino beams. In the sixties and seventies bubble chamber experiments were performed with the participation of Rome experimental groups.

From the seventies Neutrino experiments were performed with electronic detectors at CERN, Japan and USA. In addition to accelerator experiments in Rome physics department we have experiment on the Majorana or Dirac
nature of neutrinos and experiments measuring neutrinos from astrophysical sources.

We will describe the participation of the ’Sapienza’ University and INFN in these experiments.

The theorist contribution to neutrino physics is given in next section

1.1 Theoretical contributions to neutrino physics

Important theoretical contributions have been made in the past in the Department (before Istituto) and are still going on. Main fields of research in particle physics are: weak interactions, electroweak theory and atmospheric and cosmic radiation.

For what concerns neutrino physics we give numbers (approximate) of published papers and arxiv preprint hep-ph in authors alphabetic order a also mentioning a few selected papers.

Guido Altarelli (4 papers) Must Heavy Leptons have their own neutrino (Phys. Lett. B67 463, 1977. Charmed quarks and asymptotic freedom in neutrino scattering (phys LettB 48 435 1974) Altarelli has worked in Rome until 1976, he has then continued his activity in CERN and Roma3 University.

Nicola Cabibbo (9 papers): CP violation in neutrino interactions (XII Neutrino Telescope Workshop, 1978). Time reversal violation in neutrino interactions (Phys. Lett. B72 333 1978). Neutrino processes in a compound model for the nucleon (Phys. Lett. B48 435 1974). (Paper in
collaboration With L. Maiani and G. Altarelli)

Daniele Fargion. (19 papers) Ultra high energy neutrino scattering (Astrophysics J. 517 725 1999). Discovering ultra high energy neutrinos (Astrophysics J. 570 908 2002)

Paolo Lipari (21 papers): The neutrino cross section of upward going muons( Phys. rev. Lett.74,4384,1995). Comparison of $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_s$ (Phys. Rev. D58 073005 1998)

Maurizio Lusignoli(24 papers): Fresh look at neutrino oscillations (Nuclear Physics B168 1980). Neutrino decay and atmospheric neutrinos (Phys. lett. B462 109 1999)

Luciano Maiani (11 papers) Theory of interactions of neutrino with matter. (Neutrino physics, editor K. Winter, pg 278 1981) . Electromagnetic corrections to neutrino processes (Nucl. Phys. B186 1981)

Important contributions were also made by Guido Martinelli, Barbara Mele and Silvano Petrarca.

2 History

The Department of Physics (initially Istituto) was built in 1935 and the Fermi group moved in from the old Institute of Via Panisperna. The group was composed of E.Fermi, E.Amaldi, B.Pontecorvo, F.Rasetti and E.Segre.

The impact of Pontecorvo on neutrino physics, with his activity described in [1], has been widely recognized in the scientific world. For example V.Telegdi once said
Almost all important ideas in neutrino physics are due to Pontecorvo

In the thirties, two fundamental contributions to particle physics were made: Fermi developed the theory of beta decay [2] and in 1934 Fermi and his group realized the fission of uranium irradiated with neutrons[3, 4]. Particle physics started with the Conversi, Pancini, Piccioni experiment that showed that the cosmic rays particles were not strongly interacting particles. They were weakly interacting particles called ’muons’. The importance of the experiment was such that it was recognized as the origin of particle physics by Luis Alvarez in his 1978 Nobel lecture. Neutrino physics started in Rome in 1975 when Marcello Conversi proposed an experiment for the detection of charmed particles in a neutrino beam. [5] Experiments with neutrino beams were performed at CERN and in the United States in the ’70s and ’80 mainly using bubble chambers. These were Gargamelle (1970-1978) and BEBC installed at the beginning of the 1970 and dismantled in 1985. In the late seventies big electronic detectors devoted to neutrino physics started:

CDHS(1977-1983)and CHARM(1978-1984) were devoted to the study of deep inelastic neutrino scattering (charged and neutral currents)

CHARM2 (1986-1990) was built to study neutrino electron elastic scattering.

The main purpose of Nomad(1994-1997) and Chorus(1992-1997) a hybrid experiment, was to look for neutrino oscil-
Rome groups participated in the CHARM, CHARM2 and CHORUS experiments.

Long baseline experiments, are experiments in which a detector is placed at several hundred km from the source of neutrinos. The large distance is needed to access the small $\Delta m^2$ region of oscillations observed in atmospheric neutrino experiments. Rome has participated in several experiments, K2K(1999-2004) designed to confirm results of atmospheric neutrinos at KEK in Japan. Rome is still participating in Opera(2008-): Observation of neutrino tau in a beam of neutrini mu CERN-Gran Sasso

T2K(2009-) at Jpark Japan: detection of $\nu_\mu$ to $\nu_e$ oscillations Finally Rome is involved in the CUORE(2008-) experiment searching for double beta decay and in astrophysical neutrino measurement in large underwater detectors, NEMO(1998-)

3 results and experiments

This section will contain results of the experiments described in the previous section, in particular

- charm physics results
- oscillations: theory, chorus, K2K, T2K and Opera
- Large detector results: charm, charm2
- Fermilab: Sciboone results
- Cuore : Search for double beta decay
- Nemo : Detection of extraterrestrial neutrinos

In the end we will recall a proposal, largely due to Rome, to check the oscillation result obtained by the LSND

3.1 Study of charm physics

The discovery in 1974 of J/ψ particle, a charm-anti charm state and then of particles containing a charm quark, were considered as proof of the existence of a new particle the Charm (C). The direct observation of their flight path was a challenge because the charmed particles had to decay weakly with lifetimes of $10^{-14}$ s, $10^{-15}$ with decay path $\lambda$ length of few $\mu$m ($\lambda = c\tau\gamma$).

The final proof of the existence of these particles had to be the measurement of their path. For this reason, Marcello Conversi proposed to observe the short life charm particles produced in neutrino interactions in experiments combining nuclear emulsions, bubble chambers and counter techniques. In fact, being a weak process, neutrinos interactions violate charm conservation and the charm particles can be produced singly in the reaction $\nu_\mu + N \rightarrow \mu + 1\text{charmed} + \text{otherhadrons}$ Experiments were made at CERN And Fermilab. In Europe a large emulsion collaboration was set up. Rome did participate under the guidance of prof. Giustina Baroni. Lifetimes of Charm particles were measured for mesons and hadrons.
3.2 Neutrino Oscillations

In this section after an introduction to neutrino oscillations we will consider the following experiments: Chorus Opera, K2K, T2K to which Rome contributed.

The value of SuperKamiokande $\Delta m^2$ for $\nu_\mu$ oscillations requires values of $L/E$ km/Gev of the order of $10^3$ km/Gev to detect oscillations, recall formula (1) of section 3.2.1.

For this reason Opera, K2k, Te2k are long baseline experiments.

3.2.1 Neutrino oscillations

Neutrino oscillations, first predicted by Bruno Pontecorvo and then observed experimentally, are a quantum mechanical process in which a neutrino created with a certain flavor can be observed later with a different flavor. The flavor eigenstates are not the mass eigenstates. The mixing matrix can be expressed in terms of three mixing angles and a phase factor.

The present experimental values for the mixing angles are\[6\]

$$\sin^2 2\theta_{12} = 0.857 \pm 0.024$$
$$\sin^2 2\theta_{23} > 0.95$$
$$\sin^2 2\theta_{13} = 0.098 \pm 0.0.012.$$  

The latter result has been obtained in the last two years using data from reactor experiment: Doublechooz \[7\], Daya Bay \[8\], Reno \[9\], accelerator: T2K \[10\].

Before there was only an upper limit CHOOZ

$$\sin^2 2\theta_{13} < 0.13 \[11\]$$
Oscillations are characterized by the mass difference for different species $\Delta m_{il}^2 = m_i^2 - m_l^2$

For three neutrinos only two independent mass differences are possible and measured. The smallest $\Delta m_{12}^2 = (7.9 \pm 0.6) \times 10^{-5} eV^2$ is measured in solar and reactor neutrino experiments and the largest $\Delta m_{23}^2 = (2.4 \pm 0.21) \times 10^{-3} eV^2$ is measured in atmospheric and accelerators neutrinos experiments. We recall that the oscillation probability for only two neutrinos can be written as

$$P = \sin^2 2\theta \sin^2 (1.27 \Delta m^2 L/E) \quad (1)$$

where $\theta$ is the mixing angle and $\Delta m^2$ is the mass squared difference of the two neutrinos, $L$ is the distance between source and detector and $E$ the energy of neutrinos. In the three neutrino mixing scheme the probability of $\nu_\mu$ to $\nu_e$ oscillations can be written in first approximations

$$P = \sin^2 2\theta_{13} \sin^2 (\vartheta_{23}) \sin^2 (1.27 \Delta m_{23}^2 L/E) \quad (2)$$

where $\vartheta_{23}$ and $\Delta m_{23}^2$ refer to the mixing of the $\nu_\mu$ to $\nu_\tau$ as seen in atmospheric and accelerators disappearance experiments while $\vartheta_{13}$ is observed in $\nu_e$ reactor experiments disappearance experiments as well in the recently observed $\nu_\mu$ to $\nu_e$ oscillations.

The complete formula of the oscillation probability (first approximation in (2)) that can be found, for example in [12], it contains the phase factor of the mixing matrix $\delta$ and terms that are sensitive to the mass hierarchy and matter effects.
The search for neutrino oscillation made in CHARM and CHARM2 did not produce any positive result.

The collaboration proposed an experiment in 1990 to look with high sensitivity for $\nu_\mu$ to $\nu_\tau$ oscillation. The experiment was approved in 1991 and the construction of the detector was completed in 1994. Data taking started in the same year and was completed in 1998. The description of the apparatus can be found [13]. The detector was a hybrid design with a large emulsion target (770 kg). Planes of high resolution fiber trackers to predict impact point of track on the emulsions were followed downstream by an electromagnetic calorimeter and a muon spectrometer. The calorimeter [14] was built by italian groups (Ferrara, Napoli, Roma).

At that time there were indication for oscillation in the deficit of neutrino emitted by the sun, while there was no evidence for $\nu_\mu$ oscillation. A motivation of the experiment can be found in ref. [15], where high values of $\Delta M^2$ and low mixing for $\nu_\mu$ to $\nu_\tau$ oscillation were predicted. This mass region was accessible in a high sensitivity experiment at CERN SPS neutrino Beam where sensitivity of $10^{-4}$ in the oscillation probability in the high mass region could be obtained in few years of running.

The final result of the experiment was published in ref [16] giving a limit of $\sin^2 2\theta_{\nu_\mu-\nu_\tau}$ of $4.4 \times 10^{-3}$ for large $\Delta m^2$.

Because of the high granularity of emulsions and the development of fast automatic measuring systems, a large
amount of charm events (2059) were found and the decays classified according to their topology. About 15 papers were published from 1998 and 2011. They included: Cross sections of charm production in anti neutrino interactions[17], properties of the $D^0$ meson [18], associated charm production [19], measurement of muonic branching ratios of charmed hadrons [20].

3.2.3 OPERA

Neutrino $\nu_\mu$ oscillations have been first observed in the disappearance mode of atmospheric neutrinos experiments. The overall picture of atmospheric, solar, accelerators and reactor experiments is consistent with the fact that the disappearance is due to $\nu_\mu$ to $\nu_\tau$ oscillation, but no direct proof has been obtained. OPERA is an experiment to detect $\nu_\tau$ from oscillations in a pure $\nu_\mu$ beam using high resolution nuclear emulsions that allow a measurement of the $\tau$ decay. The $\nu_\mu$ beam from CERN is sent to LNGS at a distance of 730 km where Opera is located. The average neutrino beam energy is 17 GeV which does not correspond to the maximum of oscillations but rather to the optimization of of the number of observable $\tau$ taking into account the threshold for $\tau$ production. The experiment detector consist of 150,000 bricks of ECC (emulsions +lead foils sandwiches) for a total mass of 1300 tons. The experiment is complemented with trackers to reconstruct charged tracks and locate the interaction vertex and followed by a muon spectrometer to measure muon mo-
mentum. The Rome group led by G.Rosa participates in the analysis of the emulsions.

The experiment started data taking in 2008 and is still running. At the moment two neutrino tau interactions have been detected \[21\]. with a background of 0.2 event

3.2.4 K2K

In 1998 evidence was presented for $\nu_\mu$ oscillation in atmospheric neutrinos \[22\]. In 1999 a long baseline accelerator experiment was started to confirm this oscillations at an accelerator neutrino beam this phenomenon. Neutrino of about 1 GeV were generated using the KEK accelerator and observed in the SuperKamiokande large water Cherenkov detector at a distance of 275 km as the far detector. The experiment had a two detector layout described in \[23\]. The near detector was composed of a large water Cherenkov detector, scintillation fiber trackers, a fine grained scintillator detector, an electromagnetic calorimeter and a muon ranger. The electromagnetic calorimeter for the Run II of the experiment was built by reusing modules of the CHORUS calorimeter. The installation of the calorimeter, calibration and running of the experiment was responsibility of the Rome group (led by L. Ludovici) which joined the experiment in 2002.

At the end of data taking in 2005 112 events were observed against an expectation of 158 in the absence of oscillations. The $\nu_\mu$ disappearance interpreted in terms of oscillation gave a value of $\Delta m^2$ in agreement with the val-
ues indicated by atmospheric neutrino experiments. \[24\]

Moreover several results have been published on neutrino cross sections using data of the close detector, we recall here the results on charged pion production \[25\] coherent pion production \[26\] the analysis of $\pi^0$ production \[27\]

### 3.2.5 T2K

Until few years ago the value of $\theta_{13}$ was unknown and only upper limits were available \[11\] The knowledge of value of this quantity is important because a not too small value opens the possibility of measuring the CP violating phase $\delta$ appearing in the mixing matrix. Many experiments are searching for this value, both reactor experiment to observe the disappearance of $\nu_e$ and accelerator experiment looking for $\nu_e$ appearance in a $\nu_\mu$ beam oscillations that are possible in a 3 flavor mixing scenario see formula (2) in section \[3.2.1\]. T2K is a search for $\nu_e$ appearance in a neutrino beam produced at JPARC numu appearance experiment. As in K2k, the far detector is SuperKamikande which sees an off-axis neutrino beam with 0.6 average neutrino energy at a baseline of 296 km tuned to the first maximum of atmospheric neutrino oscillations. The near detector located at a distance of 280 meters from the target consists of three large volume time projection chambers interleaved with two fine grained scintillator tracking detectors and a scintillating detector dedicated to $\pi^0$ detection. All of the system is embedded the CERN UA1
magnet. The idea of magnetizing the close detector by refurbishing the CERN UA1 magnet was suggested by PF Loverre (Rome). The Rome group (leader Lucio Ludovici) is now working in the analysis.

The first result based on 6 candidates was published in 2011 [10] and the present result, based on 11 $\nu_e$ events, was presented at the 2012 neutrino conference [28]

$$\sin^2 2\theta_{13} = 0.104 + 0.06 - 0.045$$

The present result is based on a value of $\delta = 0$ and of normal hierarchy.

3.3 results obtained with general purpose detectors

3.3.1 CHARM

The CHARM detector was primarily designed to investigate neutral-current interactions of high-energy neutrinos. The detector, described in [29] consisted of an ionization calorimeter target to determine the energy and the direction of the shower produced by the neutrino scattering, and of a magnetic muon spectrometer. The detector was run in the SPS neutrino beam from 1978 to 1982. The spokesman of the CHARM collaboration (acronym for CERN, Hamburg, Amsterdam, Rome, Moscow) was Klaus Winter and the Rome group was led by Bruno Borgia. The Rome group contributed to the construction of the detector, to the running of the experiment and to the analysis of the data. Results were obtained in various fields and many papers were published. We recall the measurement of the
electroweak mixing angle, a fundamental parameter of the electroweak theory. In neutrino semi leptonic interactions the collaboration measured from the ratio of neutral over charged current interactions

\[ R = \frac{\sigma_{NC}}{\sigma_{CC}} = 1/2 - \sin^2 \vartheta_w + 5/9 + \sin^4 \vartheta_w (1 + r) \]

where \( r \) is ratio of neutrino and anti neutrino cross sections a value of

\[ \sin^2(\vartheta_w) = .236 + 0.012(m_c - 1.5) \pm 0.005(\text{exp}) \pm 0.003(\text{theor}) \]

[30]. It must be noted that the result has been parametrized in term of \( m_c \), the charm quark mass.

The collaboration also measured the value of the mixing angle from the ratio of the cross sections of neutrino and anti neutrino electron scattering [31]

\[ R \frac{\sigma(\nu_{\mu}e)}{\sigma(\bar{\nu}_{\mu}e)} = 3 \frac{(1 - 4\sin^2(\vartheta_w) + 16/3\sin^2(\vartheta_w))}{(1 - 4\sin^2(\vartheta_w) + 16/\sin^2(\vartheta_w))} \]

obtaining a value of

\[ \sin^2(\vartheta_w) = .211 \pm .037(\text{stat}) \]

. A total of 83 events in the neutrino and 112 in the anti neutrino beam were observed.

Results were also obtained in the beam dump layout [32]. In this layout the proton beam was stopped in a heavy target (copper) to study prompt decays. Prompt decays were expected to be mostly to charm decays as longer living hadrons would have interacted before decaying. The result were consistent with the assumption that the prompt neutrinos did come from charm decays.
A two detector layout was made in the PS neutrino beam \[33\] searching for neutrino oscillations. A search was also made in the SPS beam \[34\]. Both searches were negative and upper limits were set as results.

### 3.3.2 CHARM2

CHARM2 was designed especially to study neutrino electron scattering.

The target material was glass and it was a massive (692 t) high granularity low Z detector. It is described in \[35\]. Its spokesman was Klaus Winter and the Rome group was led by U. Dore.

The Italian group contributed to the construction of the limited streamer counters. They were built in Italy under the supervision of the Rome group.

The study of neutrino electron scattering allowed a precise determination of the electroweak mixing from the ratio of the cross sections of neutrino and anti neutrino electron scattering. The ratio of cross sections was determined by counting the number of electron events in the neutrino (3886) and anti neutrino (4996) beams. \[36\] A value of

\[
sin^2(\theta_w) = 0.2324 \pm 0.0058(stat) \pm 0.0059(syst)
\]

was determined.

Results were also obtained on the study of dimuons, events with a first muon produced in a charged current interaction and a second one coming from the muonic decay of a charmed particle \[37\], on the determination of the
cross section of the inverse muon decay \[38\] and on the search of neutrino of \(\nu_\mu\) to \(\nu_\tau\) oscillation \[39\]. Because the short lifetime of the \(\tau\) produced by the charged current interactions of oscillated \(\nu_\tau\) the granularity of the detector did not allow a direct observation, topological arguments were used; reaching the upper limit of \(3.4.10^{-3}\) for \(sen^2\vartheta\) for \(\Delta M^2 = 25\) eV\(^2\). A different approach has been proposed, oscillations reduce the number of charged currents. For large \(\Delta m^2\) an upper limit \(sen^2\vartheta \leq 3.10^{-3}\) was set.

3.4 SCIBOONE

The experiment was dedicated to the measurement of neutrino an anti neutrino cross section at around \(1\) GeV energy. The experiment was done at the booster neutrino beam of the Fermi National Laboratory (FERMILAB). The data taking started in 2007 and finished in 2008. The Italian group leader was L. Ludovici. The experiment consisted of three subsystem: a fine grain tracker (Scibar), an electromagnetic calorimeter and a muon range detector. Scibar and the electromagnetic calorimeter constructed for the K2K experiment were transported to Fermilab and reused.

Results have been obtained on neutrino and antineutrino interactions\[40\], neutral \(\pi^0\) \[41\], coherent pion production in charged \[42\] and neutral \[43\] current production, \(K^+\) \[44\] production. Results on \(\nu_\mu\) and \(\overline{\nu}_\mu\) disappearance were obtained in a combined experiment Sciboone +Miniboone \[45\].
3.5 CUORE

The assignment of the neutrino nature, whether they are Dirac or Maiorana particles, is still an open problem. The CUORE experiment, search of the neutrinoless beta decay will tackle this problem. This process is in fact permitted for Maiorana neutrinos and forbidden for Dirac ones. The experiment situated in the Laborarori del Gran Sasso (LNGS) cavern is a large cryogenic detector built of $TeO_2$ crystals cooled at 10 mK. Results obtained in a test apparatus Cuoricinino have been published in 2006 [46].

3.6 NEMO

The search for extra galactic high energy neutrino sources is the aim of the NEMO underwater Cherenkov neutrino detector [47]. The construction of a $km^3$ detector in the northern emisphere is a goals of astro particle physics. The Rome group (leader a. Capone) is participating to the experiment. As opposed to photons and charged particles neutrinos interact only weakly and so they proceed in straight lines thus giving information on galactic and extragalactic sources. The Nemo detector, situated at a depth of 3500 m will be located in the mediteranean sea, at capo Passero near Sicily at a depth of 3500 m. The detector will have of the order of 100 vertical towers equipped with photomultipliers.
3.7 An experiment to check the LSND results

In 1996 the LSND collaboration presented results showing some evidence of $\nu_\mu$ to $\nu_e$ oscillations at a $\Delta m^2$ of the order of $\text{eV}^2$. Their final result can be found in [48]. Because there were already the indications of a two values of $\Delta m^2$, see section 3.2.1 from solar neutrinos and from atmospheric neutrino experiments, with a three neutrino model there was no room for a third value of $\Delta m^2$. This result, if confirmed, would require a fourth neutrino, which had to be sterile because of LEP limit on the light active neutrinos. Rome had a leading role in setting up a large collaboration [49] aiming to firmly confirm or refuse the LSND results.

A two detector experiment at CERN was designed, with a neutrino beam sent from the PS to a close detector at 130 m and a far one at 880 m.

The two detectors consisted of scintillation bars interleaved with iron sheets. It was a fine grain high sensitivity apparatus suitable to detect $\nu_e$. The proposal was rejected by the SPSC committee. It must be noted that the proposal was valuable, in fact after 15 years a similar proposal has been made from the Carlo Rubbia group [50]. This rejection of the proposal was noxious for the neutrino group in Rome, a large majority of persons involved in the proposal left neutrino physics.
4 Conclusions

This paper describes the evolution of experimental neutrino Physics in the Rome Sapienza Physics Department. After 40 years the activity is still continuing with Cuore, Opera, Nemo and T2K experiments.

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