Introduction

In this booklet we have recollected 3 papers written by Bruno Pontecorvo and collaborators in the fifties of the last century.
This initiative has been carried out within the activities of the “Centro Dipartimentale Bruno Pontecorvo”, CBP, of the Physics Department of the University of Pisa. The institutional task of the CBP is the recollection of the most important physics results obtained in the past century together with a study of the life and of the activities of the physicists who obtained those results. Main emphasis is devoted to the Italian physicist Bruno Pontecorvo, BP, and to his achievements in various fields of physics. Bruno, born in Pisa in 1913, was pupil in Rome of Enrico Fermi, then he went to Paris to collaborate with the couple Joliot-Curie until 1940 and, because war, refugee in USA and Canada. In the forties Pontecorvo came back to Europe after the second world war, to UK first and finally moved to Russia in 1950. It was at the physics laboratory of the Joint Institute of Nuclear Physics (JINR) of Dubna, near Moscow in USSR, that Pontecorvo obtained the major achievements in nuclear and particle physics.

The 3 papers collected in this publication were originally published in Russian (ref “titolo del libro in russo”) and now we are publishing them in a new improved english translation made by BP’s son, Gil, who is himself a physicist of the JINR Laboratory in Dubna.
The 3 articles report the measurements performed by BP and collaborators at the Dubna's SynchroCyclotron , a proton accelerator of 680 MeV in operation at JINR since 1954 (Fig. 1). Their titles are:

1)”Scattering of π^+mesons in hydrogen. II. Discussion and interpretation of the results”.

2)”Total interaction cross sections of negative π^-mesons with hydrogen in the interval of energies from 140 up to 400 MeV”.

3)”Production of π^- mesons in hydrogen and deuterium by neutrons at the energy of 400 MeV”.

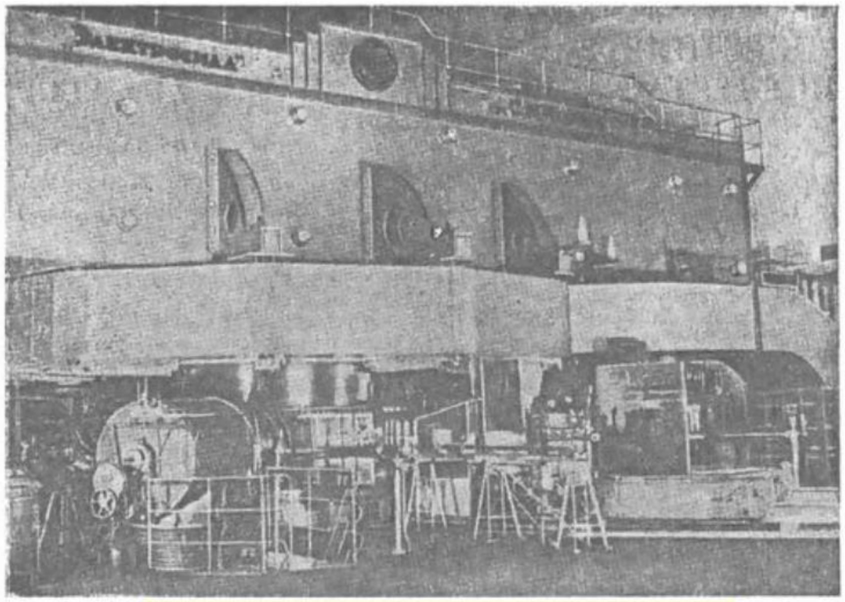

Fig. 1 The Synchrocyclotron in operation at the JINR Institute of Dubna

The JINR's proton accelerator was, at that time, the most powerful machine available in the world reaching a proton energy of 680 MeV; as a comparison the Synchrocyclotron used by Fermi at Chicago at the beginning of the 50's, allowed a maximum proton energy of 450 MeV.

The BP's papers presented here, describe the experiments carried out at Dubna to study the interactions of pions (positive and negative) with hydrogen and the production of neutral pions by the interaction of neutrons with hydrogen and deuterium.

The interactions of charged pions with hydrogen were also studied by Fermi at the Chicago synchrocyclotron, while the neutral pion production, measured by looking at the gamma-rays from the neutral pion decays, was a novelty in nuclear physics at that time.

The physics interpretation of the results of the measurements of the interactions of pions with hydrogen (i.e. with protons) used the so called "Partial Wave Analysis" (see for example : E. Fermi, "Nuclear Physics", the University of Chicago press, 1950) where the interaction is described with the help of scattering amplitudes classified in term of the angular orbital momentum (waves S,P,D,..)

total angular momentum and isotopic spin of the system (1/2, 3/2) which is assumed conserved in the pion-proton interactions.

The interest for the pion-proton interactions was triggered by puzzling experimental results showing that the positive pion-proton cross section was much higher than that for negative pion-proton interaction, despite the fact that, in the first case, only the elastic scattering was possible. An interesting explanation of this effect was that, at pion's energies around 180 MeV, a resonance could be produced: the Δ^{++}, a member of the Δ–particle family, whose existence was already suggested, but not proven, by the measurements of Fermi and collaborators: H.L. Anderson et al. : Phys.Rev.,85, 936(1952) and Phys. Rev. , 91, 155 (1953). If the resonances existed, the positive pion-proton, the negative pion-proton (via charge-exchange) and negative pion-proton (elastic-scattering) cross-sections were predicted to be in the ratios: 9:2:1.)

Fig.2 E. Fermi at the Control Room of the Chicago Synchrocyclotron. 1951

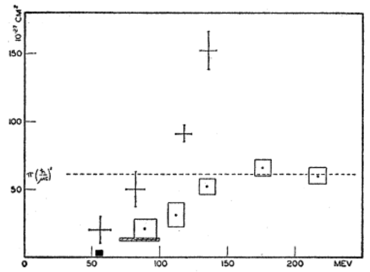

FIG. 1. Total cross sections of negative pions in hydrogen (sides of the rectangle represent the error) and positive pions in hydrogen (arms of the cross represent the error). The cross-hatched rectangle is the Columbia result. The black square is the Brookhaven result and does not include the charge exchange contribution.

Fig.3

The results of the Fermi’s experiments in Chicago showed indeed that the cross sections of negative pion and positive pion interactions with protons increased with the pion energy reaching a maximum at about 180 MeV (see Fig. 3). But, unfortunately, the available energy was, especially for positive pions, not sufficient to establish a clear resonant shape around the maximum of the cross sections. On the other hand, the ratio of cross sections between positive and negative pion-proton roughly seemed to be in agreement with the prescription 9:2:1.

Moreover also the amplitude phase shifts determination obtained by the Fermi's group with the partial wave analysis at various pion energies, was not conclusive. In fact, in case of resonance, the phase shift should become 90 degrees at the top of the resonance cross section, but, again, at Chicago, the measurements were not performed in a sufficiently large pion energy-range. The phase shift analysis is important to establish the nature of the resonance in terms of spin and isospin.

The paper by BP and Mukhin ,1), addresses specifically this point: they performed a careful analysis of the phases of the pion+-proton interactions, obtained from angular distribution measurements, at various pion energies and under the hypothesis of several configurations of isotopic spins and total angular momenta. The results of the phase analysis is that the phase shift corresponding to a state with total angular momentum 3/2 and isospin 3/2, obtained at a pion energy of about 190 MeV, is about 90 degrees, confirming the existence of a wide resonance with a mass of about 1200 MeV produced at pion energies between 170 and 200 MeV, as already suggested, but not confirmed, by Fermi and collaborators in previous articles.

Also the measurements of negative pion-proton cross sections at pion energies between 140 and 400 MeV, paper 2), indicate the presence of a wide, but clear resonance, at a central value of about 190 MeV of the pion energy, as shown in Fig. 4a and Fig.4b obtained from Table 1 of the paper 2).
In both distributions, fitted respectively with a Lorentzian (Breit-Wigner) shape and a Gaussian shape, the center of the fitted function is at 191 MeV and the half-width half-maximum of both distributions is about 50 MeV. An easy calculation shows that the invariant mass of the pion-proton interaction for a pion of 191 GeV interacting with a proton at rest, is 1235 MeV, corresponding to the central value of produced resonance mass. It should be also noted that the measured width is dominated by the natural width of the Δ_0

resonance since the experimental mass resolution is estimated to be only 5 MeV. The measured peak position and the width of the resonance can be directly compared with the best value known today of 1232 and 58 MeV, respectively, of the mass and of the width of the Δ_0 ("Review of Particle Physics", Tanabashi et al. (Particle Data Group)Phys. Rev. D 98, 030001 – Published 17 August 2018).).

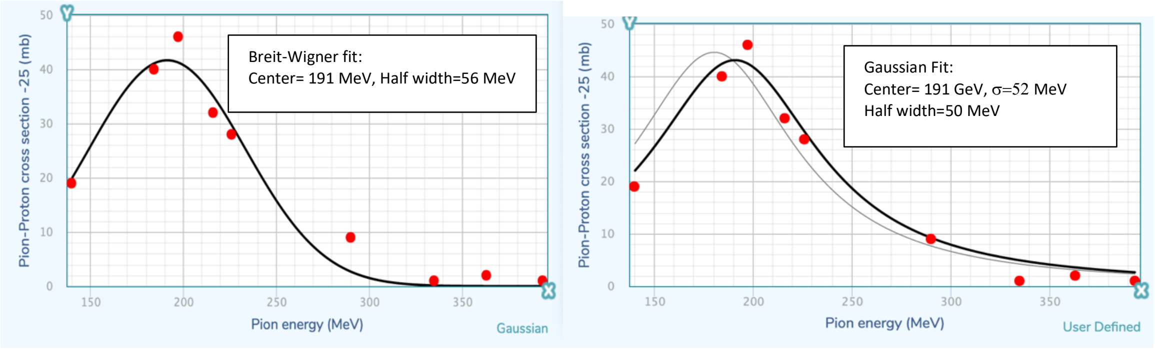

Fig. 4 Negative pion-proton cross section measured at the JINR Synchrocyclotron: a) the datapoints are fitted by a Breit-Wigner distribution; b) the fit is performed with a Gaussian distribution.

The dominance of the positive pion-proton cross section relative to the negative one was also confirmed by BP et al (JETP, 1956, vol. 9, p. 371).

The way to describe the strong interactions between pions and nucleons and nucleon-nucleon (as well as of all hadrons) in the 50's and 60's of the past century, was based only on models relying on symmetry conservation, general characteristics of the interaction amplitudes and asymptotic theorems. A dynamical field theory of the interaction was still missing. Instead, a field theory: the Quantum Electro Dynamics, was already developed for the electromagnetic interactions.

The results obtained in the pion-proton interactions by BP and collaborators, within the models available at that time, despite the prudent conclusions by the authors of paper 2), provide a strong support for the existence of a new resonance: the delta baryon particle. The Δ's are found to have isospin 3/2 and spin 3/2 so appearing in 4 possible states: Δ^{++},Δ^{+},Δ^{0},Δ^{-} and corresponding antiparticles. The mass and the width of these particles are known today to be 1232 and 117 MeV (full width) respectively (Particle Data Group Phys. Rev. D98, 030001 (2018)).

The discovery of the Δ's resonances has played a very important role in particle physics for two reasons:

-the Δ's, are members of the baryon decuplet, with strangeness 0, in the quark classification of baryons, providing a strong support to the validity of the Gell-Mann-Zweig quark model which predicts the baryons to be composed by 3 quarks;

-it was responsible of a new puzzling situation in the 70's. In fact the Δ^{++} and Δ^{-} resulted to be composed by 3 identical quarks: (uuu) and (ddd), respectively, with identical ½ spin orientation. Such particle states are in flagrant conflict with the Pauli principle which states the wavefunction to be antisymmetric under the exchange of fermion-pair. Motivated also by this contradiction, in the 70's it was proposed the quarks carry a new quantum number named color, which, for each quark, can appear in 3 possibilities, e.g. red, blue and green, thus making it possible for the wave function, within the SU(3) color symmetry, to be antisymmetric in the exchange. This new color symmetry allowed the construction of a new field theory describing the strong interactions between quarks (and gluons) named Quantum Chromodynamics.

The paper 3) describes the measurements of the differential and total cross sections for production of neutral pions in interactions of neutrons with hydrogen (protons) and deuterium (deutons). As matter of fact only single photons were detected in the final state (the π^0, instead, decays into photon-pairs); moreover, the error in the cross-section determination was large: about 50%. Nevertheless the authors correctly, were able to exclude a simple radiative electromagnetic gamma-production, in favor of a much larger meson (via strong interaction) production.

An interesting consequence of this measurements was obtained by comparing the proton-proton, neutron-neutron, neutron-proton cross-sections to produce charged pions or neutral pions. The scheme proposed, supported by the experimental evidence, was that the most probable isospin state of the initial nucleon-pairs is: T_I=1, while the final isospin of the nucleon pairs is null. We know that strong interactions, such those producing charged and neutral pions, conserve isospin, so the scheme proposed points to the correct assignement of isospin T=1 to pions (the isospin of nucleons is ½) which represents another interesting contribute to the description of hadrons, baryons and mesons, as made by 3 quarks (baryons) and quark-antiquark pairs (mesons).

In conclusion we think that, although not decisive, the results obtained by Bruno Pontecorvo and collaborators in the fifties of the last century at the Dubna's Synchrocyclotron presented in these articles*, represent an important contribution to the knowledge of the elementary particle physics, laying the foundations for important following developments.

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*For a more complete collection of Bruno Pontecorvo's papers in English, consult:

"Bruno Pontecorvo selected scientific works" second edition edited by: S.M. Bilenky, T.D. Blokhinstseva, V.A. Matveev, I.G. Pokrovskaya and M.G. Sapozhnikov.

Societa’ Italiana di Fisica , 2013

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