The Scientific Heritage of Bruno Pontecorvo

The Triumph of Neutrino Oscillations

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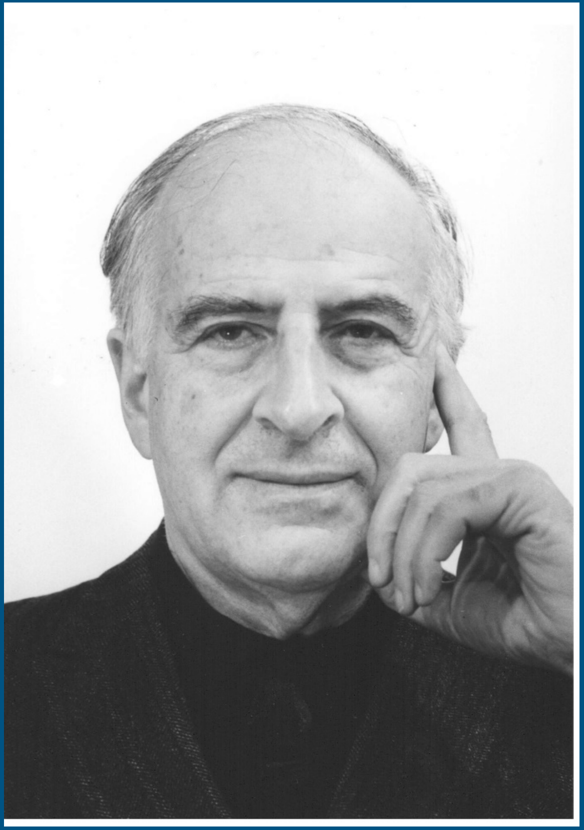
Pisa, 13 October 2015

In 2013 the centenary of Bruno Pontecorvo was celebrated by series of events

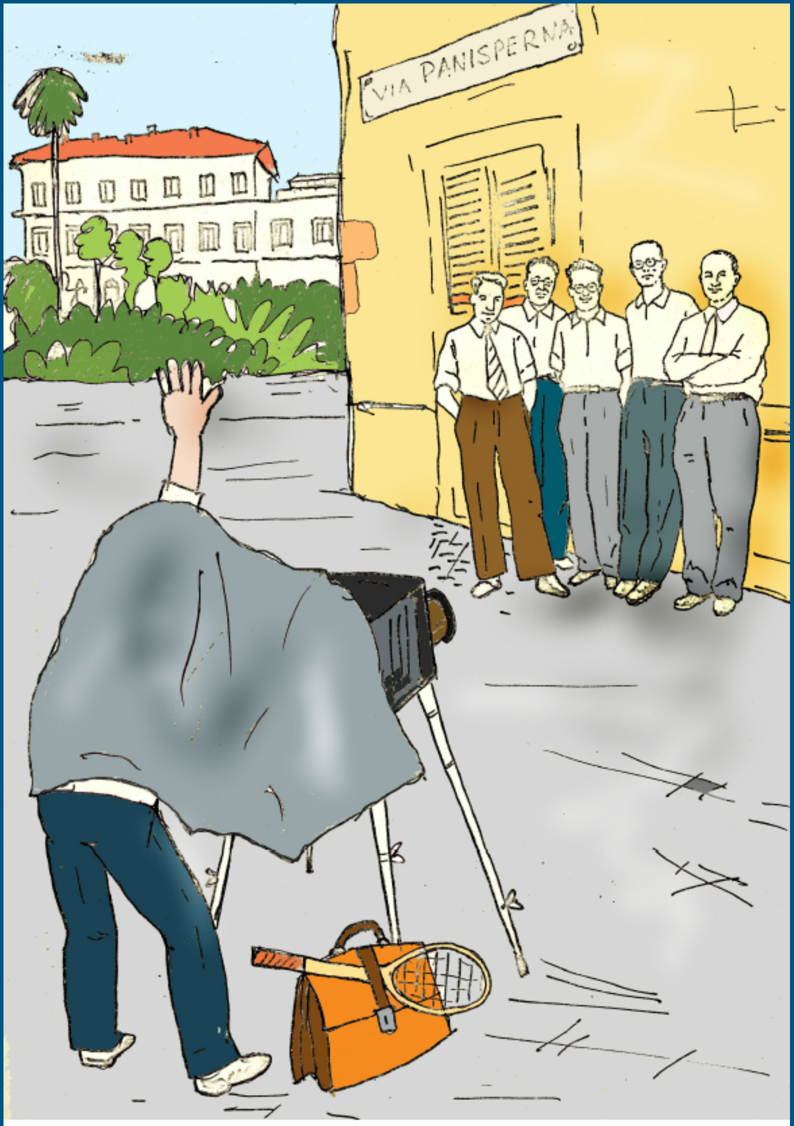


Born on 22 August 1913 in Pisa

- ✓ V International Pontecorvo School on Neutrino Physics, 6-16 September, 2012, Alushta, Crimea.
- ✓ Ceremony of EPS Historic Site Opening in Dubna, 22 February, 2013.
- ✓ XVI Lomonosov Conference, 22-28 August 2013, Moscow.
- ✓ Scientific Session of RAS on Perspectives in Neutrino and Astroparticle Physics, 2-3 September, 2013, Dubna.
- ✓ The Legacy of Bruno Pontecorvo: the Man and the Scientist Conference, 11-12 September, 2013, Rome.
- ✓ Pontecorvo 100: Symposium on the centennial of the birth of Bruno Pontecorvo. 18-20 September, 2013, Pisa.

1931-1936 – B.Pontecorvo was a student and then a member of the widely known group of “Via Panisperna boys”.

Under the guidance of Enrico Fermi B.Pontecorvo studied the properties of slow neutrons and took part in the discovery of the phenomenon neutron moderation



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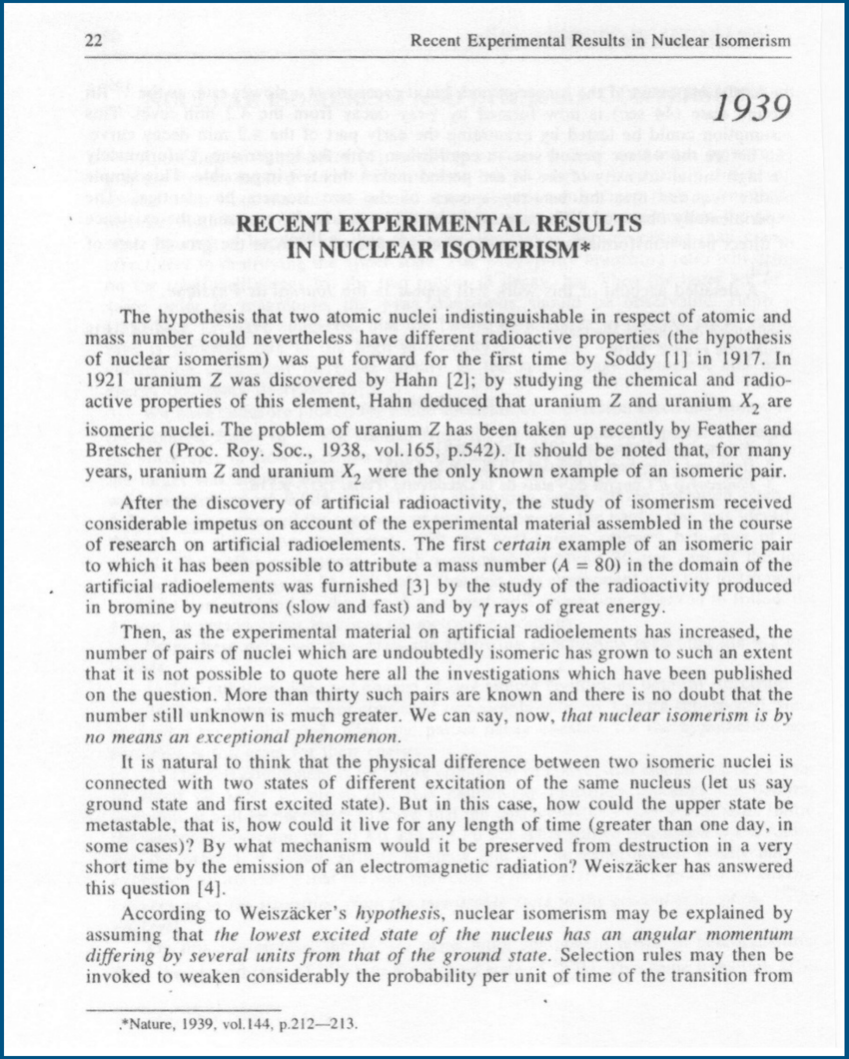
1936-1940 – B.Pontecorvo worked with F.Joliot-Curie at the Radium Institute in Paris.



1939

RECENT EXPERIMENTAL RESULTS IN NUCLEAR ISOMERISM*

The hypothesis that two atomic nuclei indistinguishable in respect of atomic and mass number could nevertheless have different radioactive properties (the hypothesis of nuclear isomerism) was put forward for the first time by Soddy [1] in 1917. In 1921 uranium Z was discovered by Hahn [2]; by studying the chemical and radioactive properties of this element, Hahn deduced that uranium Z and uranium X_2 are isomeric nuclei. The problem of uranium Z has been taken up recently by Feather and Bretscher (Proc. Roy. Soc., 1938, vol.165, p.542). It should be noted that, for many years, uranium Z and uranium X_2 were the only known example of an isomeric pair.

After the discovery of artificial radioactivity, the study of isomerism received considerable impetus on account of the experimental material assembled in the course of research on artificial radioelements. The first *certain* example of an isomeric pair to which it has been possible to attribute a mass number ($A = 80$) in the domain of the artificial radioelements was furnished [3] by the study of the radioactivity produced in bromine by neutrons (slow and fast) and by γ rays of great energy.

Then, as the experimental material on artificial radioelements has increased, the number of pairs of nuclei which are undoubtedly isomeric has grown to such an extent that it is not possible to quote here all the investigations which have been published on the question. More than thirty such pairs are known and there is no doubt that the number still unknown is much greater. We can say, now, *that nuclear isomerism is by no means an exceptional phenomenon.*

It is natural to think that the physical difference between two isomeric nuclei is connected with two states of different excitation of the same nucleus (let us say ground state and first excited state). But in this case, how could the upper state be metastable, that is, how could it live for any length of time (greater than one day, in some cases)? By what mechanism would it be preserved from destruction in a very short time by the emission of an electromagnetic radiation? Weiszäcker has answered this question [4].

According to Weiszäcker's *hypothesis*, nuclear isomerism may be explained by assuming that *the lowest excited state of the nucleus has an angular momentum differing by several units from that of the ground state.* Selection rules may then be invoked to weaken considerably the probability per unit of time of the transition from

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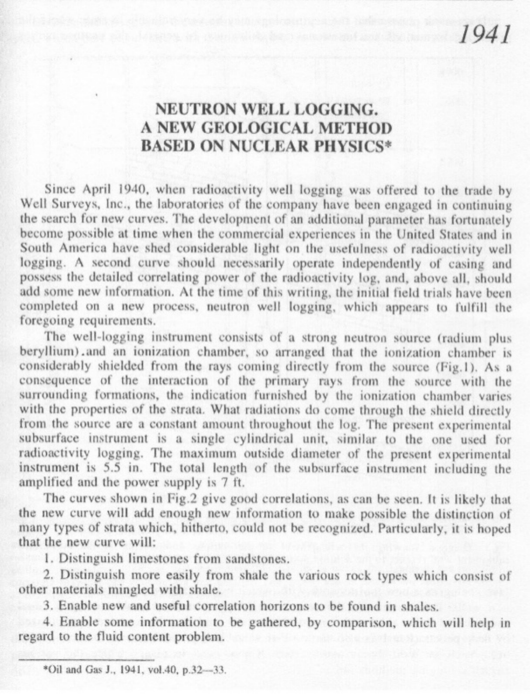
.*Nature, 1939, vol.144, p.212—213.

The research of nuclear isomerism led him to the discovery of a New phenomenon of nuclear phosphorescence (excitation of metastable states of a beta-stable isotopes with MeV gamma-quanta)

1940-1942 – a private company in the USA
B.Pontecorvo studied geophysical methods of oil wells' probing

He suggested and worked out a new effective method of oil exploration in 1941 – the neutron logging that tops the chronology of important applications of neutron



Neutron Well Logging. A New Geological Method Based on Nuclear Physics 27

1941

NEUTRON WELL LOGGING.
A NEW GEOLOGICAL METHOD
BASED ON NUCLEAR PHYSICS*

Since April 1940, when radioactivity well logging was offered to the trade by Well Surveys, Inc., the laboratories of the company have been engaged in continuing the search for new curves. The development of an additional parameter has fortunately become possible at time when the commercial experiences in the United States and in South America have shed considerable light on the usefulness of radioactivity well logging. A second curve should necessarily operate independently of casing and possess the detailed correlating power of the radioactivity log, and, above all, should add some new information. At the time of this writing, the initial field trials have been completed on a new process, neutron well logging, which appears to fulfill the foregoing requirements.

The well-logging instrument consists of a strong neutron source (radium plus beryllium).and an ionization chamber, so arranged that the ionization chamber is considerably shielded from the rays coming directly from the source (Fig.1). As a consequence of the interaction of the primary rays from the source with the surrounding formations, the indication furnished by the ionization chamber varies with the properties of the strata. What radiations do come through the shield directly from the source are a constant amount throughout the log. The present experimental subsurface instrument is a single cylindrical unit, similar to the one used for radioactivity logging. The maximum outside diameter of the present experimental instrument is 5.5 in. The total length of the subsurface instrument including the amplified and the power supply is 7 ft.

The curves shown in Fig.2 give good correlations, as can be seen. It is likely that the new curve will add enough new information to make possible the distinction of many types of strata which, hitherto, could not be recognized. Particularly, it is hoped that the new curve will:

1. Distinguish limestones from sandstones.
2. Distinguish more easily from shale the various rock types which consist of other materials mingled with shale.
3. Enable new and useful correlation horizons to be found in shales.
4. Enable some information to be gathered, by comparison, which will help in regard to the fluid content problem.

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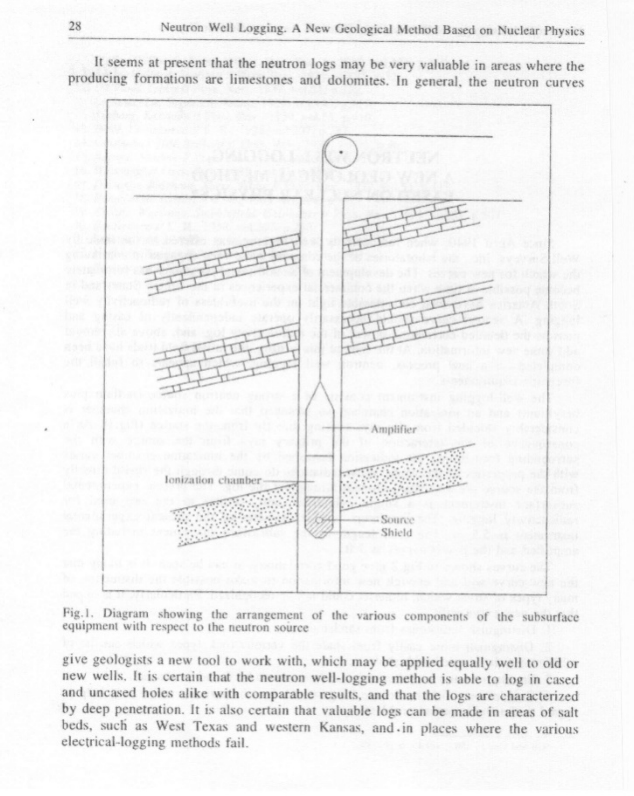
*Oil and Gas J., 1941, vol.40, p.32—33.



28 Neutron Well Logging. A New Geological Method Based on Nuclear Physics

It seems at present that the neutron logs may be very valuable in areas where the producing formations are limestones and dolomites. In general, the neutron curves

Fig.1. Diagram showing the arrangement of the various components of the subsurface equipment with respect to the neutron source

give geologists a new tool to work with, which may be applied equally well to old or new wells. It is certain that the neutron well-logging method is able to log in cased and uncased holes alike with comparable results, and that the logs are characterized by deep penetration. It is also certain that valuable logs can be made in areas of salt beds, such as West Texas and western Kansas, and.in places where the various electrical-logging methods fail.

1947 – First realized that coupling constants of muon and electron interaction with nucleons are the same. Starting point of lepton universality.

1948 – Proportional counter with high gain for low background measurements

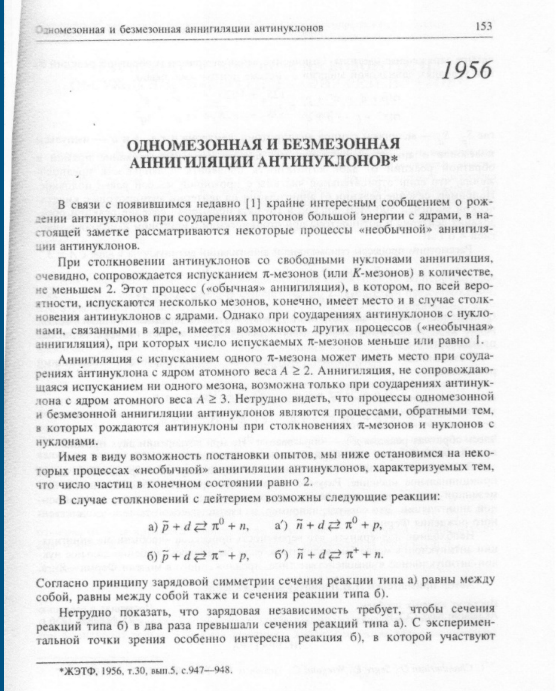
1949 – Measurement of tritium beta spectrum and first limit on neutrino mass

August 1950 – B.Pontecorvo came to live in USSR

1951-1953 – Measurement of neutral pion production at Dubna synchrocyclotron

1954-1957 – Measurememnt of piP and piN interactions

1953 - Bruno Pontecorvo expressed a hypothesis on simultaneous production of kaons and hyperons and together with L.B.Okun came to a conclusion that the quantum number “strangeness” can change by not more than 1 in weak processes.



Одномезонная и безмезонная аннигиляции антинуклонов 153

1956

ОДНОМЕЗОННАЯ И БЕЗМЕЗОННАЯ АННИГИЛЯЦИИ АНТИНУКЛОНОВ*

В связи с появившимся недавно [1] крайне интересным сообщением о рождении антинуклонов при соударениях протонов большой энергии с ядрами, в настоящей заметке рассматриваются некоторые процессы «необычной» аннигиляции антинуклонов.

При столкновении антинуклонов со свободными нуклонами аннигиляция, очевидно, сопровождается испусканием π-мезонов (или K-мезонов) в количестве, не меньшем 2. Этот процесс («обычная» аннигиляция), в котором, по всей вероятности, испускаются несколько мезонов, конечно, имеет место и в случае столкновения антинуклонов с ядрами. Однако при соударениях антинуклонов с нуклонами, связанными в ядре, имеется возможность других процессов («необычная» аннигиляция), при которых число испускаемых π-мезонов меньше или равно 1.

Аннигиляция с испусканием одного π-мезона может иметь место при соударениях антинуклона с ядром атомного веса $A \geq 2$. Аннигиляция, не сопровождающаяся испусканием ни одного мезона, возможна только при соударениях антинуклона с ядром атомного веса $A \geq 3$. Нетрудно видеть, что процессы одномезонной и безмезонной аннигиляции антинуклонов являются процессами, обратными тем, в которых рождаются антинуклоны при столкновениях π-мезонов и нуклонов с нуклонами.

Имея в виду возможность постановки опытов, мы ниже остановимся на некоторых процессах «необычной» аннигиляции антинуклонов, характеризуемых тем, что число частиц в конечном состоянии равно 2.

В случае столкновений с дейтерием возможны следующие реакции:

$$\text{а) } \tilde{p} + d \rightleftarrows \pi^0 + n, \qquad \text{а}') \ \tilde{n} + d \rightleftarrows \pi^0 + p,$$

$$\text{б) } \tilde{p} + d \rightleftarrows \pi^- + p, \qquad \text{б}') \ \tilde{n} + d \rightleftarrows \pi^+ + n.$$

Согласно принципу зарядовой симметрии сечения реакции типа а) равны между собой, равны между собой также и сечения реакции типа б).

Нетрудно показать, что зарядовая независимость требует, чтобы сечения реакций типа б) в два раза превышали сечения реакций типа а). С экспериментальной точки зрения особенно интересна реакция б), в которой участвуют

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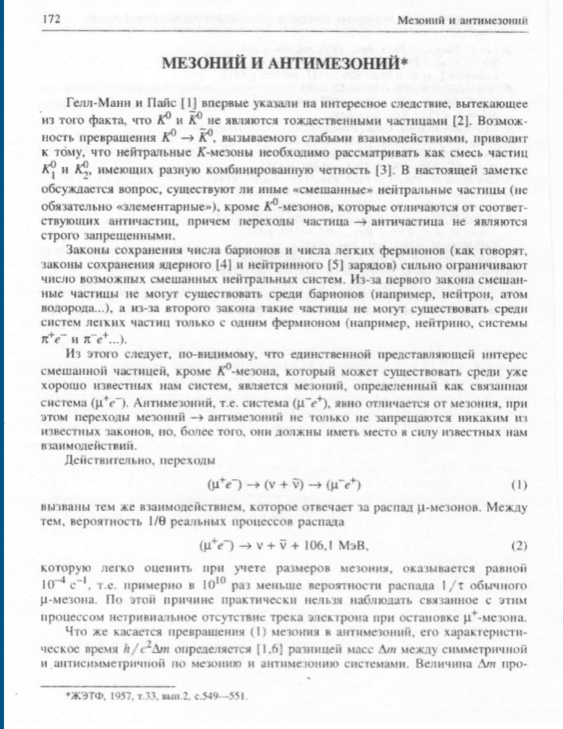
*ЖЭТФ, 1956, т.30, вып.5, с.947—948.

1956 - B.Pontecorvo published a paper on a possibility of exotic annihilation reactions forbidden on one nucleon but allowed when the antiproton annihilates in the nucleus. This type of reaction is known today as “the Pontecorvo reaction”; it gives new opportunities for meson spectroscopy.

In 1957 B.Pontecorvo for the first time expressed the idea on possible existence of muonium transitions (μ+e-) into antimuonium (μ-e+). In this process the lepton numbers of particles change immediately by 2 and, consequently, this process is totally forbidden in the Standard Model. Discussing the muonium-antimuonium transitions, B.Pontecorvo presupposed that oscillations can occur not only in the case of bosons (neutral kaons and muonia), but also in the case of electrically neutral fermions. It was the birth of the neutrino oscillation hypothesis.

It was founded on the deep analogy of the weak interaction of leptons and hadrons that motivated Bruno Pontecorvo long before the occurrence of the quark-lepton symmetry in the modern Standard Model.

B.Pontecorvo regarded neutrino oscillations as a phenomenon analogous to neutral kaon oscillations possible only in the case when neutrinos possess small, different from zero, masses.



МЕЗОНИЙ И АНТИМЕЗОНИЙ*

Гелл-Манн и Пайс [1] впервые указали на интересное следствие, вытекающее из того факта, что K^0 и $\bar{K}^0$ не являются тождественными частицами [2]. Возможность превращения $K^0 \to \bar{K}^0$, вызываемого слабыми взаимодействиями, приводит к тому, что нейтральные K-мезоны необходимо рассматривать как смесь частиц K_1^0 и K_2^0, имеющих разную комбинированную четность [3]. В настоящей заметке обсуждается вопрос, существуют ли иные «смешанные» нейтральные частицы (не обязательно «элементарные»), кроме K^0-мезонов, которые отличаются от соответствующих античастиц, причем переходы частица → античастица не являются строго запрещенными.

Законы сохранения числа барионов и числа легких фермионов (как говорят, законы сохранения ядерного [4] и нейтринного [5] зарядов) сильно ограничивают число возможных смешанных нейтральных систем. Из-за первого закона смешанные частицы не могут существовать среди барионов (например, нейтрон, атом водорода...), а из-за второго закона такие частицы не могут существовать среди систем легких частиц только с одним фермионом (например, нейтрино, системы π^+e^- и π^-e^+...).

Из этого следует, по-видимому, что единственной представляющей интерес смешанной частицей, кроме K^0-мезона, который может существовать среди уже хорошо известных нам систем, является мезоний, определенный как связанная система (μ^+e^-). Антимезоний, т.е. система (μ^-e^+), явно отличается от мезония, при этом переходы мезоний → антимезоний не только не запрещаются никаким из известных законов, но, более того, они должны иметь место в силу известных нам взаимодействий.

Действительно, переходы

$$(\mu^+e^-) \to (\nu + \tilde{\nu}) \to (\mu^-e^+) \tag{1}$$

вызваны тем же взаимодействием, которое отвечает за распад μ-мезонов. Между тем, вероятность $1/\theta$ реальных процессов распада

$$(\mu^+e^-) \to \nu + \tilde{\nu} + 106{,}1\ \text{МэВ}, \tag{2}$$

которую легко оценить при учете размеров мезония, оказывается равной 10^{-4} с^{-1}, т.е. примерно в 10^{10} раз меньше вероятности распада $1/\tau$ обычного μ-мезона. По этой причине практически нельзя наблюдать связанное с этим процессом нетривиальное отсутствие трека электрона при остановке μ^+-мезона.

Что же касается превращения (1) мезония в антимезоний, его характеристическое время $h/c^2\Delta m$ определяется [1,6] разницей масс Δm между симметричной и антисимметричной по мезонию и антимезонию системами. Величина Δm про-

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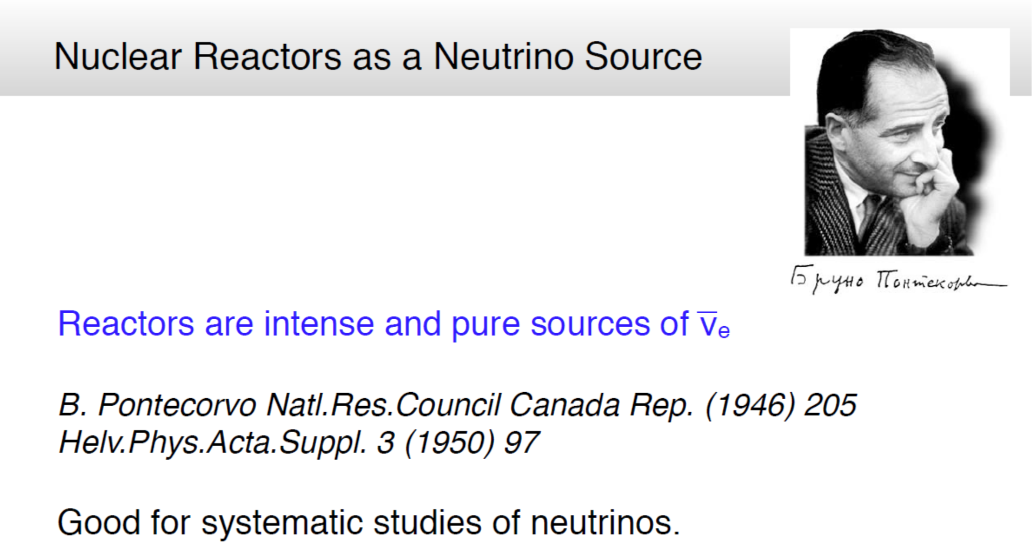
*ЖЭТФ, 1957, т.33, вып.2, с.549—551.

In 1930 a new particle (neutrino) was introduced by W.Pauli as a solution of a problem of continuous beta-spectrum, which was thought to contradict to the energy conservation law.

Pauli himself was in doubt that this new particle will be ever detected experimentally.

Estimated in 1934 by Bethe and Peierls very small (~ 10^{-44} cm^2) cross section for neutrino interaction just strengthen these doubts.



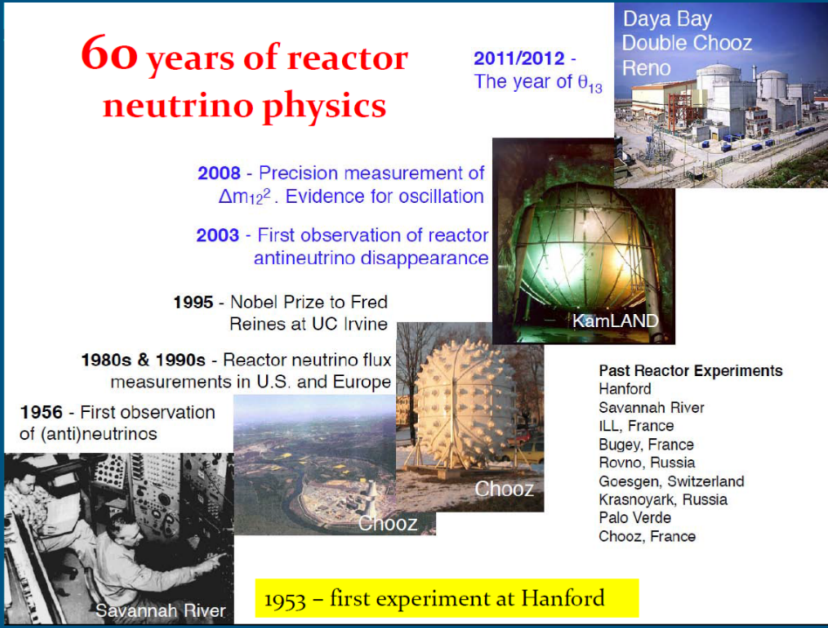
Nuclear Reactors as a Neutrino Source

Бруно Понтекорво

Reactors are intense and pure sources of $\overline{\nu}_e$

B. Pontecorvo Natl.Res.Council Canada Rep. (1946) 205
Helv.Phys.Acta.Suppl. 3 (1950) 97

Good for systematic studies of neutrinos.



60 years of reactor neutrino physics

2011/2012 - The year of θ_{13}

2008 - Precision measurement of Δm_{12}^2. Evidence for oscillation

2003 - First observation of reactor antineutrino disappearance

1995 - Nobel Prize to Fred Reines at UC Irvine

1980s & 1990s - Reactor neutrino flux measurements in U.S. and Europe

1956 - First observation of (anti)neutrinos

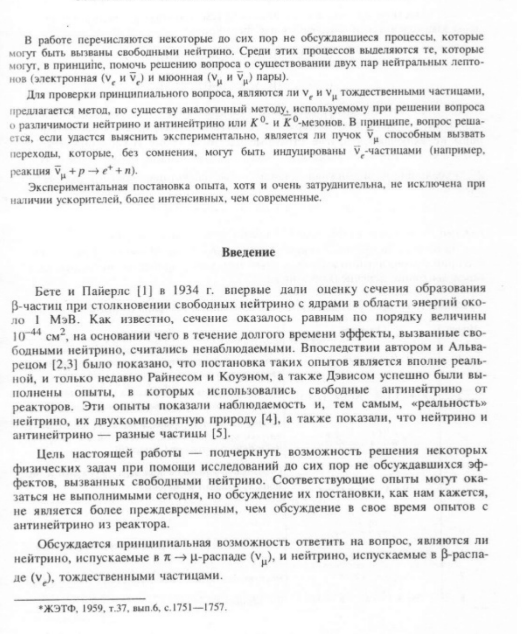
Past Reactor Experiments
Hanford
Savannah River
ILL, France
Bugey, France
Rovno, Russia
Goesgen, Switzerland
Krasnoyark, Russia
Palo Verde
Chooz, France

1953 – first experiment at Hanford

$\nu_\mu \neq \nu_e$

Based on the absence of a certain decay channels a very important new concept of a “Lepton number ” (and later “Individual (flavor) Lepton number”) was introduced in the early 1950s. It followed from this concept that electron and muon neutrinos should be a different particles.

In the paper “Electron and Muon Neutrinos” (1959) B.Pontecorvo showed that neutrinos from the accelerator can be detected with big detectors and proposed an experiment that could give an answer to the question if electron and muon neutrinos differed from each other.



ЭЛЕКТРОННЫЕ И МЮОННЫЕ НЕЙТРИНО*

В работе перечисляются некоторые до сих пор не обсуждавшиеся процессы, которые могут быть вызваны свободными нейтрино. Среди этих процессов выделяются те, которые могут, в принципе, помочь решению вопроса о существовании двух пар нейтральных лептонов (электронная (ν_e и $\bar{\nu}_e$) и мюонная (ν_μ и $\bar{\nu}_\mu$) пары).

Для проверки принципиального вопроса, являются ли ν_e и ν_μ тождественными частицами, предлагается метод, по существу аналогичный методу, используемому при решении вопроса о различимости нейтрино и антинейтрино или K^0- и $\bar{K}^0$-мезонов. В принципе, вопрос решается, если удастся выяснить экспериментально, является ли пучок $\bar{\nu}_\mu$ способным вызвать переходы, которые, без сомнения, могут быть индуцированы $\bar{\nu}_e$-частицами (например, реакция $\bar{\nu}_\mu + p \to e^+ + n$).

Экспериментальная постановка опыта, хотя и очень затруднительна, не исключена при наличии ускорителей, более интенсивных, чем современные.

Введение

Бете и Пайерлс [1] в 1934 г. впервые дали оценку сечения образования β-частиц при столкновении свободных нейтрино с ядрами в области энергий около 1 МэВ. Как известно, сечение оказалось равным по порядку величины 10^{-44} см^2, на основании чего в течение долгого времени эффекты, вызванные свободными нейтрино, считались ненаблюдаемыми. Впоследствии автором и Альварецом [2,3] было показано, что постановка таких опытов является вполне реальной, и только недавно Райнесом и Коуэном, а также Дэвисом успешно были выполнены опыты, в которых использовались свободные антинейтрино от реакторов. Эти опыты показали наблюдаемость и, тем самым, «реальность» нейтрино, их двухкомпонентную природу [4], а также показали, что нейтрино и антинейтрино — разные частицы [5].

Цель настоящей работы — подчеркнуть возможность решения некоторых физических задач при помощи исследований до сих пор не обсуждавшихся эффектов, вызванных свободными нейтрино. Соответствующие опыты могут оказаться не выполнимыми сегодня, но обсуждение их постановки, как нам кажется, не является более преждевременным, чем обсуждение в свое время опытов с антинейтрино из реактора.

Обсуждается принципиальная возможность ответить на вопрос, являются ли нейтрино, испускаемые в $\pi \to \mu$-распаде (ν_μ), и нейтрино, испускаемые в β-распаде (ν_e), тождественными частицами.

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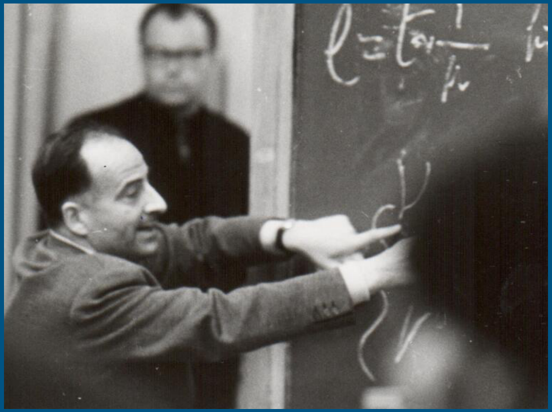
*ЖЭТФ, 1959, т.37, вып.6, с.1751—1757.



$$\bar{\nu} + p \to \mu^+ + n$$

and NOT

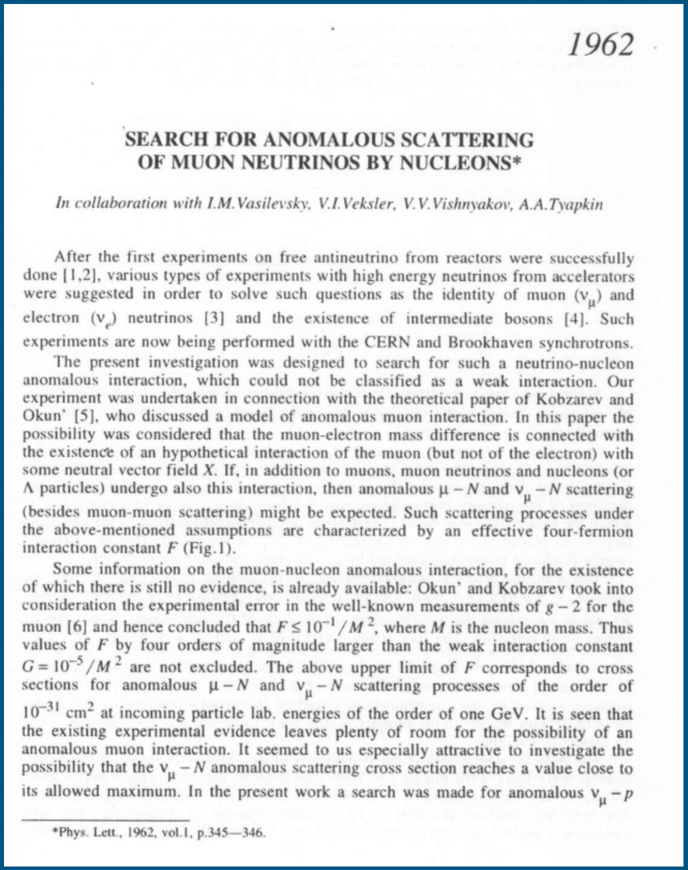
$$\bar{\nu} + p \to e^+ + n$$

This experiment was performed in 1962 at BNL showing that electron and muon neutrinos are different particles. (Nobel Prize 1988: L.M.Lederman, M.Schwartz and J.Steinberger).

1961 - on the initiative of B.Pontecorvo, an attempt was taken at the JINR synchrophasotron to detect the reaction of neutral weak currents

$$\nu_\mu + N \rightarrow \nu_\mu + N,$$

that were later discovered in 1973 at CERN with much more intense neutrino beams.



1962

SEARCH FOR ANOMALOUS SCATTERING OF MUON NEUTRINOS BY NUCLEONS*

In collaboration with I.M.Vasilevsky, V.I.Veksler, V.V.Vishnyakov, A.A.Tyapkin

After the first experiments on free antineutrino from reactors were successfully done [1,2], various types of experiments with high energy neutrinos from accelerators were suggested in order to solve such questions as the identity of muon (ν_μ) and electron (ν_e) neutrinos [3] and the existence of intermediate bosons [4]. Such experiments are now being performed with the CERN and Brookhaven synchrotrons.

The present investigation was designed to search for such a neutrino-nucleon anomalous interaction, which could not be classified as a weak interaction. Our experiment was undertaken in connection with the theoretical paper of Kobzarev and Okun' [5], who discussed a model of anomalous muon interaction. In this paper the possibility was considered that the muon-electron mass difference is connected with the existence of an hypothetical interaction of the muon (but not of the electron) with some neutral vector field X. If, in addition to muons, muon neutrinos and nucleons (or Λ particles) undergo also this interaction, then anomalous $\mu - N$ and $\nu_\mu - N$ scattering (besides muon-muon scattering) might be expected. Such scattering processes under the above-mentioned assumptions are characterized by an effective four-fermion interaction constant F (Fig.1).

Some information on the muon-nucleon anomalous interaction, for the existence of which there is still no evidence, is already available: Okun' and Kobzarev took into consideration the experimental error in the well-known measurements of $g - 2$ for the muon [6] and hence concluded that $F \leq 10^{-1}/M^2$, where M is the nucleon mass. Thus values of F by four orders of magnitude larger than the weak interaction constant $G = 10^{-5}/M^2$ are not excluded. The above upper limit of F corresponds to cross sections for anomalous $\mu - N$ and $\nu_\mu - N$ scattering processes of the order of 10^{-31} cm^2 at incoming particle lab. energies of the order of one GeV. It is seen that the existing experimental evidence leaves plenty of room for the possibility of an anomalous muon interaction. It seemed to us especially attractive to investigate the possibility that the $\nu_\mu - N$ anomalous scattering cross section reaches a value close to its allowed maximum. In the present work a search was made for anomalous $\nu_\mu - p$

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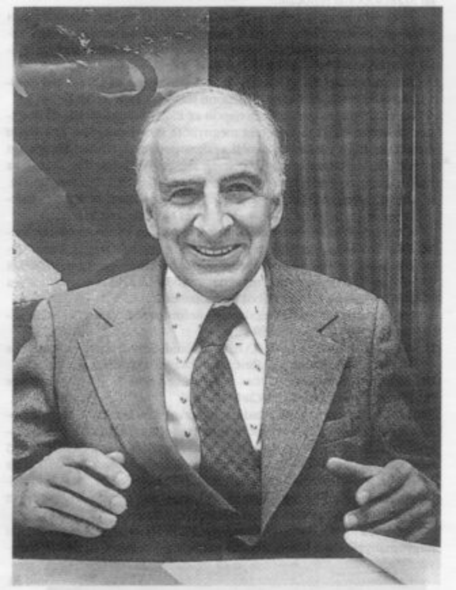
*Phys. Lett., 1962, vol.1, p.345—346.

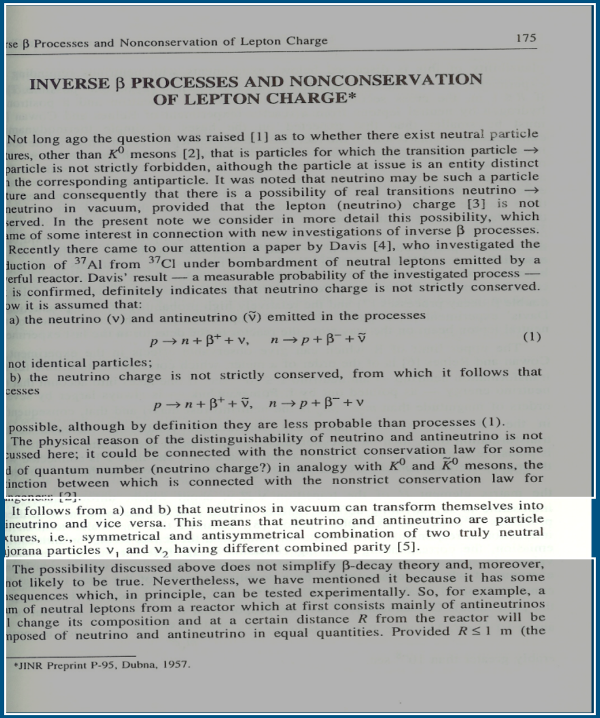
Genesis of Neutrino Oscillations

In the Standard Model, flavor lepton numbers are conserved and neutrinos are massless.



Already in 1957, based on the deep analogy to the phenomenon of neutral kaon oscillations, Pontecorvo suggested the possibility of neutrino-antineutrino oscillations.

In 1962, after the discovery of a muon neutrino, Maki, Nakagawa and Sakata discussed the possibility that electron and muon neutrinos were a mixture of two neutrino mass states.



rse β Processes and Nonconservation of Lepton Charge 175

INVERSE β PROCESSES AND NONCONSERVATION OF LEPTON CHARGE*

Not long ago the question was raised [1] as to whether there exist neutral particle tures, other than K^0 mesons [2], that is particles for which the transition particle → particle is not strictly forbidden, although the particle at issue is an entity distinct the corresponding antiparticle. It was noted that neutrino may be such a particle ture and consequently that there is a possibility of real transitions neutrino → neutrino in vacuum, provided that the lepton (neutrino) charge [3] is not served. In the present note we consider in more detail this possibility, which me of some interest in connection with new investigations of inverse β processes.

Recently there came to our attention a paper by Davis [4], who investigated the duction of ^{37}Al from ^{37}Cl under bombardment of neutral leptons emitted by a erful reactor. Davis' result — a measurable probability of the investigated process — is confirmed, definitely indicates that neutrino charge is not strictly conserved. ow it is assumed that:

a) the neutrino (ν) and antineutrino ($\tilde{\nu}$) emitted in the processes

$$p \to n + \beta^+ + \nu, \quad n \to p + \beta^- + \tilde{\nu} \qquad (1)$$

not identical particles;

b) the neutrino charge is not strictly conserved, from which it follows that cesses

$$p \to n + \beta^+ + \tilde{\nu}, \quad n \to p + \beta^- + \nu$$

possible, although by definition they are less probable than processes (1).

The physical reason of the distinguishability of neutrino and antineutrino is not cussed here; it could be connected with the nonstrict conservation law for some d of quantum number (neutrino charge?) in analogy with K^0 and $\tilde{K}^0$ mesons, the inction between which is connected with the nonstrict conservation law for ngeness [2].

It follows from a) and b) that neutrinos in vacuum can transform themselves into ineutrino and vice versa. This means that neutrino and antineutrino are particle tures, i.e., symmetrical and antisymmetrical combination of two truly neutral jorana particles ν_1 and ν_2 having different combined parity [5].

The possibility discussed above does not simplify β-decay theory and, moreover, not likely to be true. Nevertheless, we have mentioned it because it has some sequences which, in principle, can be tested experimentally. So, for example, a m of neutral leptons from a reactor which at first consists mainly of antineutrinos l change its composition and at a certain distance R from the reactor will be nposed of neutrino and antineutrino in equal quantities. Provided $R \leq 1$ m (the

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*JINR Preprint P-95, Dubna, 1957.

However, the first phenomenological model for electron and muon neutrino flavor mixing and oscillations was worked out by Pontecorvo in 1968 and later improved by Gribov and Pontecorvo in 1969, suggesting oscillations as a possible solution to the solar neutrino problem.

Detection of Solar Neutrinos and Oscillations

According to the existing model the energy at the Sun is produced from chains of thermonuclear reactions, where also electron neutrinos are produced.

Already in 1946 Pontecorvo realized that this neutrino flux will be the probe for verification of energy production mechanism.

He suggested a method to detect neutrinos by the extraction of an argon isotope that was produced at the inverse beta decay reaction:

(neutrino + ^{37}Cl → ^{37}Ar + electron)

1946

INVERSE β PROCESS*

Introduction

The Fermi theory of the β disintegration is not yet in a final stage: not only detailed problems are to be solved, but also the fundamental assumption — the neutrino hypothesis — has not yet been definitely proven. I will recall briefly the main experimental facts which have led Pauli to propose the neutrino hypothesis.

1. In a β disintegration, the atomic nucleus *Z* changes by one unit, while the mass number does not change.

2. The β spectrum is continuous, while the parent and the daughter states correspond to well defined energy values of the nuclei *Z* and *Z* ± 1.

3. The difference in energy between the initial and final states involved in a β transition is equal to the *upper* limit of the continuous spectrum.

We see that the fundamental facts can be reconciled only with one of the following alternative assumptions:

i. The law of the conservation of the energy does not hold in a single β process.

ii. The law of the conservation of the energy is valid, but a new hypothetical particle, undetectable in any calorimetric measurement — the neutrino — is emitted together with a β particle in a β transition, in such a way that the energy available in such transition is shared between the electron and the neutrino. This suggestion was made by Pauli and on this basis Fermi has built a consistent quantitative theory of the β disintegration. In addition to the difficulties already mentioned, the assumption ii removes some difficulties connected with the conservation of the spin and of the type of statistics of which we cannot speak here. The main neutrino properties follow «by definition» and are: zero charge, spin 1/2 and Fermi's statistics. The problem of the β disintegration has been attacked experimentally in many ways:

(a) β spectroscopy, i.e., study of the form of the β spectrum, the relationship between the energy release and the probability of disintegration, the ratio of positron to electron emission in cases where both electrons and positrons can be emitted, the ratio of the number of the K-capture transitions to positron transitions.

(b) Neutron Decay. This fundamental β transition, the transformation of a free neutron into a proton, has not yet been detected. Plans for its detection, as well as for the study of the angular distribution of the proton and electron emitted, have been made in several laboratories in the U.S.A. and in the Chalk River Laboratory.

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*National Reserach Council of Canada, Division of Atomic Energy, Chalk River, 1946, Report PD-205. This version was kindly provided by Prof. W.F.Davidson.

ons produced by betatrons or synchrotrons may easily satisfy this
g sources of high energy neutrinos are not available, so that the
f importance in a neutrino experiment.

ground (i.e., the production of element *Z* ± 1 by other causes than the
s) must be as small as possible.

An Example

everal elements which can be used for neutrino radiation in the
igation. Chlorine and Bromine, for example, fulfil reasonably well the
ns. The reactions of interest would be:

Cl → $\beta^- + {}^{37}$Ar　　$\nu + {}^{79,81}\mathrm{Br} \rightarrow \beta^- + {}^{79,81}\mathrm{Kr}$
→ ^{37}Cl　　$^{79,81}\mathrm{Kr} \rightarrow {}^{79,81}\mathrm{Br}$
s; *K* capture)　　(34 h; emission of positrons of 0.4 MeV)

The experiment with Chlorine, for example, would consist in irradiating with neutrinos a large volume of Chlorine or Carbon Tetra-Chloride, for a time of the order of one month, and extracting the radioactive ^{37}Ar from such volume by boiling. The radioactive argon would be introduced inside a small counter; the counting efficiency is close to 100%, because of the high Auger electron yield. Conditions 1, 2, 3, 4 are reasonably fulfilled in this example. It can be shown also that condition 5, implying a relatively low background, is fulfilled.

Causes other than inverse processes capable of producing the radioelement looked for are:

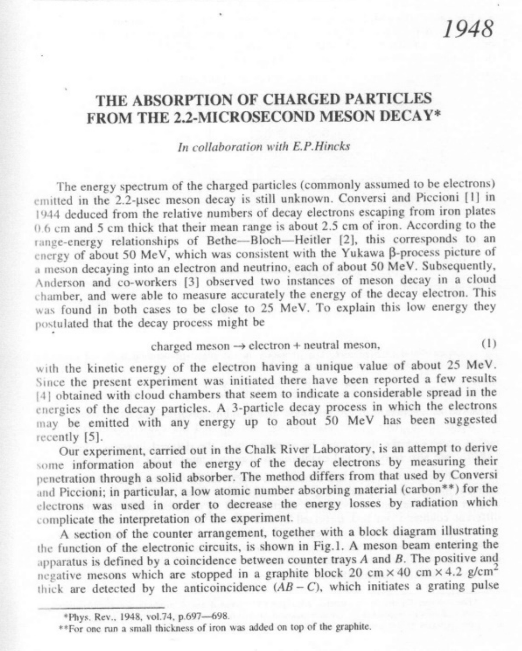
(a) (*n*, *p*) Processes and Nuclear Explosions. The production of background by (*n*, *p*) process against the nucleus bombarded is zero if the particular inverse β process selected involves the emission of a negatron rather than the emission of a positron. This is the case in the inverse β process which would produce ^{37}Ar from ^{37}Cl. Similar arguments show that «cosmic ray stars» cannot produce a direct background of ^{37}Ar from ^{37}Cl. As for (*n*, *p*) processes in impurities, the fact that ^{37}K does not exist in nature rules out this possibility.

(b) (*n*, γ) Process. This effect can produce background only through impurities. In principle at least, it can be reduced by addition of neutron absorbing material. In the case considered, ^{37}Ar could be produced by absorption of neutrons in ^{36}Ar present to an extent of 0.3% in natural argon still present as contamination. It is estimated that (*n*, 2*n*) effects, again through impurities, would not produce high background.

(c) (*p*, *n*) Effects. These effects are estimated to be very small. They would arise from cosmic rays, and are consequently independent of the neutrino strength used. They could be investigated in a blank experiment.

Now the whole world knows this phenomenon as the radiochemical chlorine-argon method to detect neutrinos from the Sun.

In 1948 B.Pontecorvo designed a proportional counter of a small size with a big signal amplification. While applying it, he observed for the first time in 1949 the nuclear capture of L-electrons in argon and made the first measurement of the tritium beta spectrum from which the first restriction on mass of the electron neutrino of less than 500 eV was obtained.



1948

THE ABSORPTION OF CHARGED PARTICLES FROM THE 2.2-MICROSECOND MESON DECAY*

In collaboration with E.P.Hincks

The energy spectrum of the charged particles (commonly assumed to be electrons) emitted in the 2.2-μsec meson decay is still unknown. Conversi and Piccioni [1] in 1944 deduced from the relative numbers of decay electrons escaping from iron plates 0.6 cm and 5 cm thick that their mean range is about 2.5 cm of iron. According to the range-energy relationships of Bethe—Bloch—Heitler [2], this corresponds to an energy of about 50 MeV, which was consistent with the Yukawa β-process picture of a meson decaying into an electron and neutrino, each of about 50 MeV. Subsequently, Anderson and co-workers [3] observed two instances of meson decay in a cloud chamber, and were able to measure accurately the energy of the decay electron. This was found in both cases to be close to 25 MeV. To explain this low energy they postulated that the decay process might be

$$\text{charged meson} \rightarrow \text{electron} + \text{neutral meson}, \qquad (1)$$

with the kinetic energy of the electron having a unique value of about 25 MeV. Since the present experiment was initiated there have been reported a few results [4] obtained with cloud chambers that seem to indicate a considerable spread in the energies of the decay particles. A 3-particle decay process in which the electrons may be emitted with any energy up to about 50 MeV has been suggested recently [5].

Our experiment, carried out in the Chalk River Laboratory, is an attempt to derive some information about the energy of the decay electrons by measuring their penetration through a solid absorber. The method differs from that used by Conversi and Piccioni; in particular, a low atomic number absorbing material (carbon**) for the electrons was used in order to decrease the energy losses by radiation which complicate the interpretation of the experiment.

A section of the counter arrangement, together with a block diagram illustrating the function of the electronic circuits, is shown in Fig.1. A meson beam entering the apparatus is defined by a coincidence between counter trays A and B. The positive and negative mesons which are stopped in a graphite block 20 cm × 40 cm × 4.2 g/cm^2 thick are detected by the anticoincidence $(AB-C)$, which initiates a grating pulse

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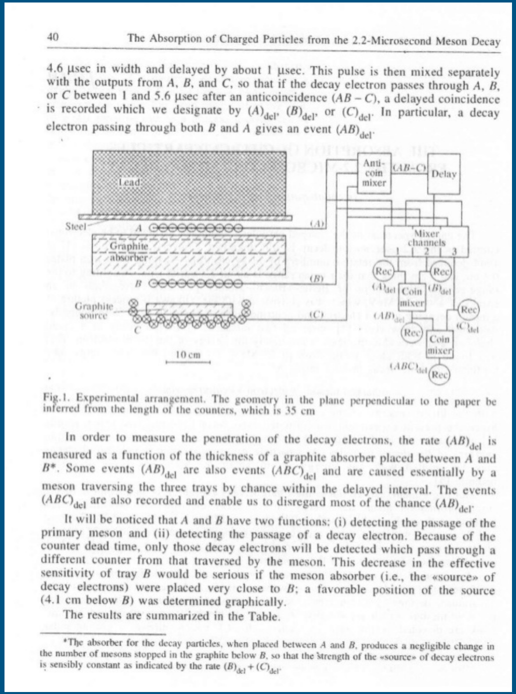
*Phys. Rev., 1948, vol.74, p.697—698.

**For one run a small thickness of iron was added on top of the graphite.



4.6 μsec in width and delayed by about 1 μsec. This pulse is then mixed separately with the outputs from A, B, and C, so that if the decay electron passes through A, B, or C between 1 and 5.6 μsec after an anticoincidence $(AB-C)$, a delayed coincidence is recorded which we designate by $(A)_{del}$, $(B)_{del}$, or $(C)_{del}$. In particular, a decay electron passing through both B and A gives an event $(AB)_{del}$.

Fig.1. Experimental arrangement. The geometry in the plane perpendicular to the paper be inferred from the length of the counters, which is 35 cm

In order to measure the penetration of the decay electrons, the rate $(AB)_{del}$ is measured as a function of the thickness of a graphite absorber placed between A and B*. Some events $(AB)_{del}$ are also events $(ABC)_{del}$ and are caused essentially by a meson traversing the three trays by chance within the delayed interval. The events $(ABC)_{del}$ are also recorded and enable us to disregard most of the chance $(AB)_{del}$.

It will be noticed that A and B have two functions: (i) detecting the passage of the primary meson and (ii) detecting the passage of a decay electron. Because of the counter dead time, only those decay electrons will be detected which pass through a different counter from that traversed by the meson. This decrease in the effective sensitivity of tray B would be serious if the meson absorber (i.e., the «source» of decay electrons) were placed very close to B; a favorable position of the source (4.1 cm below B) was determined graphically.

The results are summarized in the Table.

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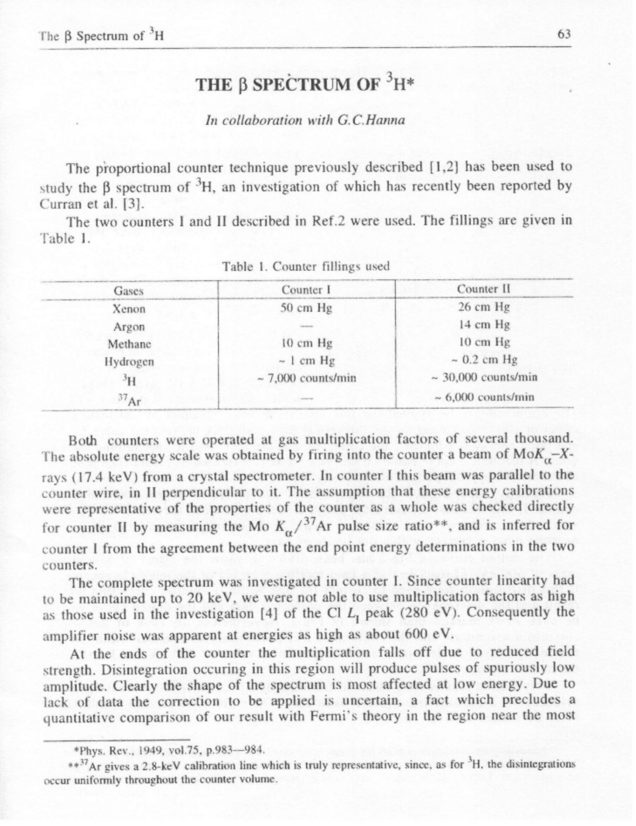
*The absorber for the decay particles, when placed between A and B, produces a negligible change in the number of mesons stopped in the graphite below B, so that the strength of the «source» of decay electrons is sensibly constant as indicated by the rate $(B)_{del} + (C)_{del}$.



THE β SPECTRUM OF ^{3}H*

In collaboration with G.C.Hanna

The proportional counter technique previously described [1,2] has been used to study the β spectrum of ^{3}H, an investigation of which has recently been reported by Curran et al. [3].

The two counters I and II described in Ref.2 were used. The fillings are given in Table 1.

Table 1. Counter fillings used

Gases	Counter I	Counter II
Xenon	50 cm Hg	26 cm Hg
Argon	—	14 cm Hg
Methane	10 cm Hg	10 cm Hg
Hydrogen	~ 1 cm Hg	~ 0.2 cm Hg
^{3}H	~ 7,000 counts/min	~ 30,000 counts/min
^{37}Ar	—	~ 6,000 counts/min

Both counters were operated at gas multiplication factors of several thousand. The absolute energy scale was obtained by firing into the counter a beam of MoK_α–X-rays (17.4 keV) from a crystal spectrometer. In counter I this beam was parallel to the counter wire, in II perpendicular to it. The assumption that these energy calibrations were representative of the properties of the counter as a whole was checked directly for counter II by measuring the Mo $K_\alpha/^{37}$Ar pulse size ratio**, and is inferred for counter I from the agreement between the end point energy determinations in the two counters.

The complete spectrum was investigated in counter I. Since counter linearity had to be maintained up to 20 keV, we were not able to use multiplication factors as high as those used in the investigation [4] of the Cl L_1 peak (280 eV). Consequently the amplifier noise was apparent at energies as high as about 600 eV.

At the ends of the counter the multiplication falls off due to reduced field strength. Disintegration occuring in this region will produce pulses of spuriously low amplitude. Clearly the shape of the spectrum is most affected at low energy. Due to lack of data the correction to be applied is uncertain, a fact which precludes a quantitative comparison of our result with Fermi's theory in the region near the most

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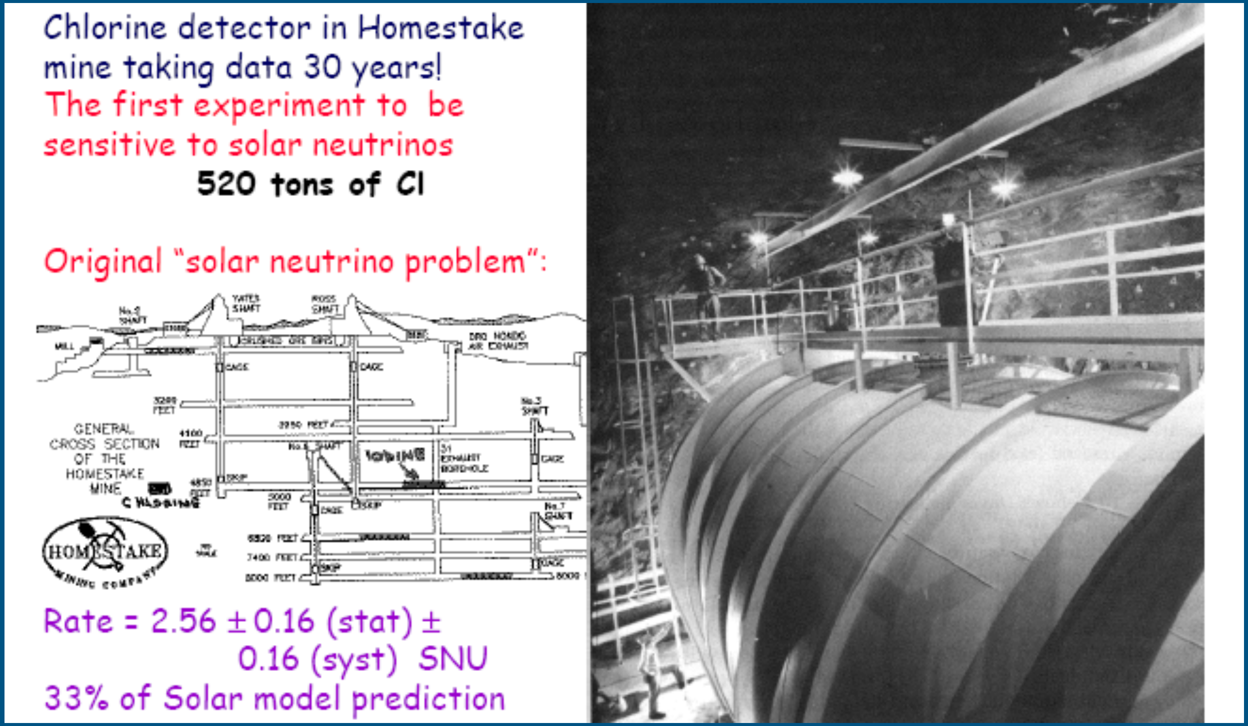
*Phys. Rev., 1949, vol.75, p.983—984.

**^{37}Ar gives a 2.8-keV calibration line which is truly representative, since, as for ^{3}H, the disintegrations occur uniformly throughout the counter volume.

Detection of Solar Neutrinos and Oscillations

The first solar neutrino detector based on Pontecorvo radiochemical method was constructed in the 1960s by R.Davis (Nobel Prize 2002) and operated for ~25 years.



Chlorine detector in Homestake mine taking data 30 years!

The first experiment to be sensitive to solar neutrinos

520 tons of Cl

Original "solar neutrino problem":

Rate = 2.56 ± 0.16 (stat) ± 0.16 (syst) SNU

33% of Solar model prediction

Deficit of solar neutrinos had already a very plausible explanation by oscillations, however, it was not clear whether the SSM is precise, especially, because Homestake had a high detection threshold and measured small fraction of the neutrino flux from the Sun.

Detection of Solar Neutrinos and Oscillations

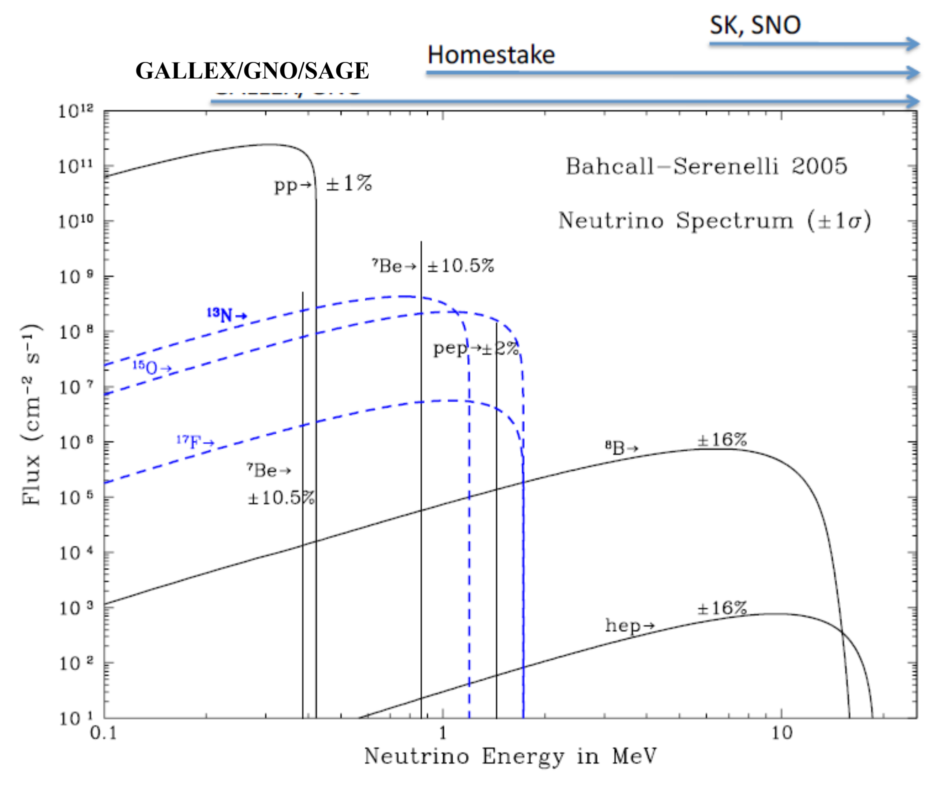
Another radiochemical method was used by GALLEX/GNO experiments at Gran Sasso and SAGE at Baksan Laboratory

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

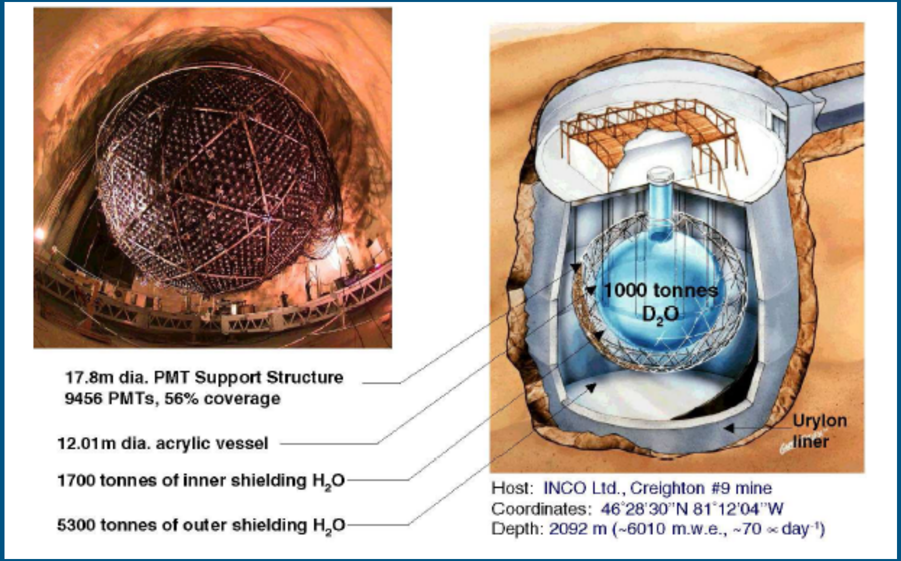
Also the water Cherenkov detectors Kamiokande and SK have measured the neutrino flux from the Sun

All of the above experiments were detecting the deficit of solar neutrinos

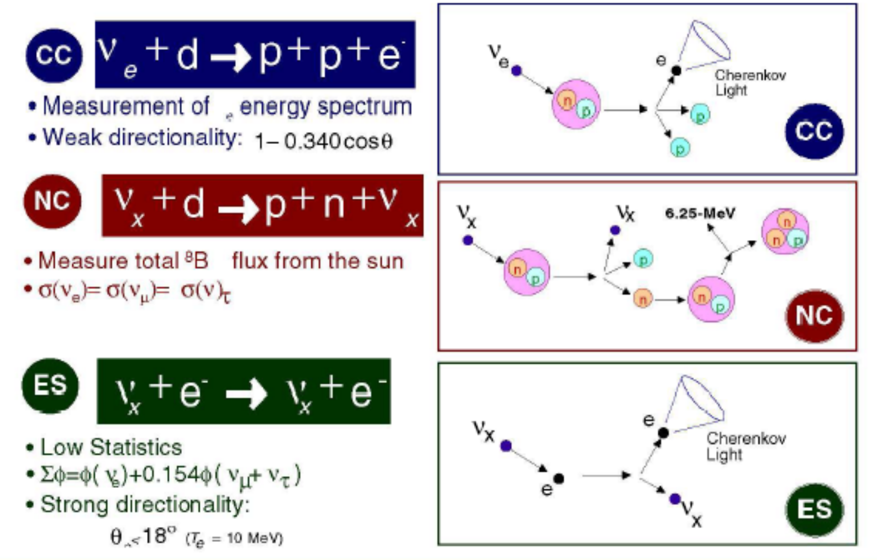
It came out that for explaining this deficit by oscillations also the, so-called, matter effect proposed by Mikheev, Smirnov and Wolfenstein (MSW) was essential to be accounted for.



SNO Results



Host: INCO Ltd., Creighton #9 mine
Coordinates: 46°28'30"N 81°12'04"W
Depth: 2092 m (~6010 m.w.e., ~70 ∝ day⁻¹)



CC $\nu_e + d \rightarrow p + p + e^-$

- Measurement of ν_e energy spectrum
- Weak directionality: $1 - 0.340\cos\theta$

NC $\nu_x + d \rightarrow p + n + \nu_x$

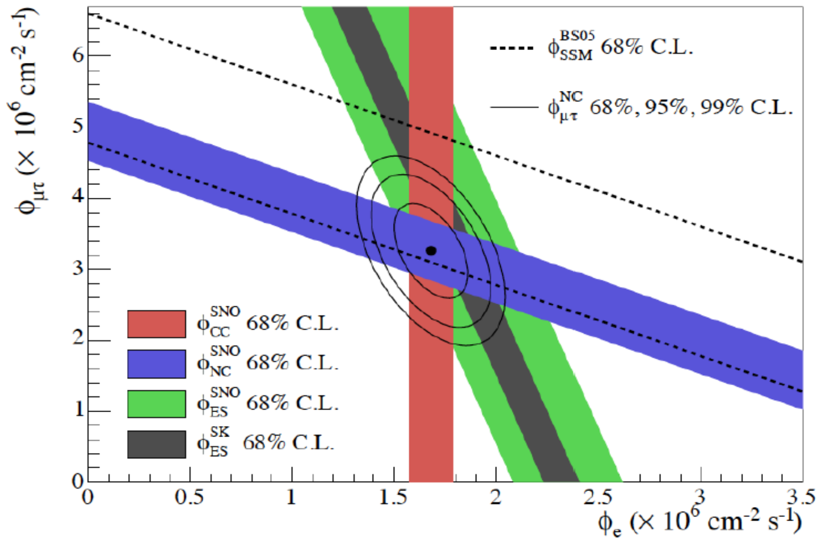
- Measure total ^8B flux from the sun
- $\sigma(\nu_e) = \sigma(\nu_\mu) = \sigma(\nu_\tau)$

ES $\nu_x + e^- \rightarrow \nu_x + e^-$

- Low Statistics
- $\Sigma\phi = \phi(\nu_e) + 0.154\phi(\nu_\mu + \nu_\tau)$
- Strong directionality:

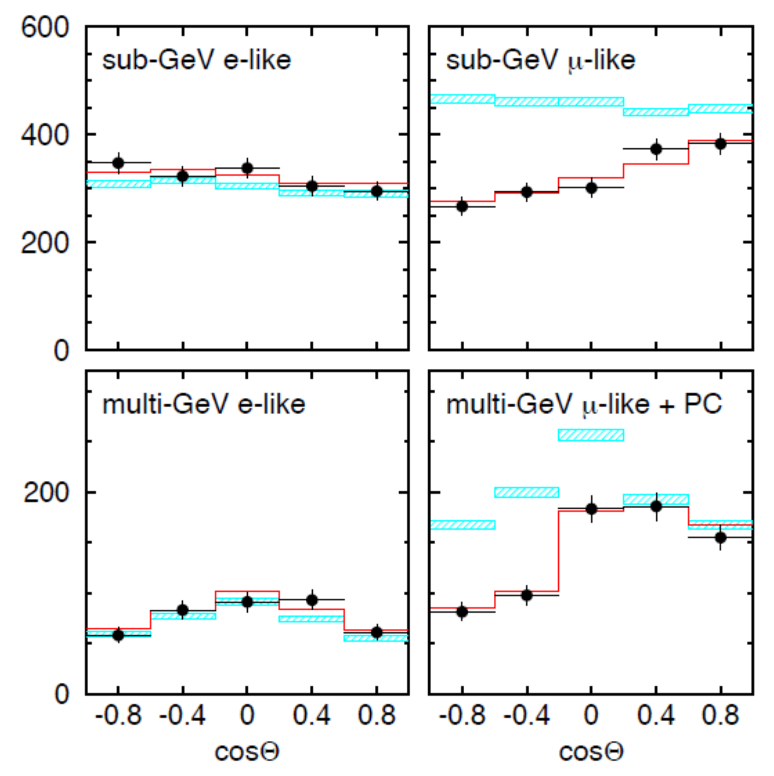
$\theta_{\odot} < 18^\circ$ (T_e = 10 MeV)

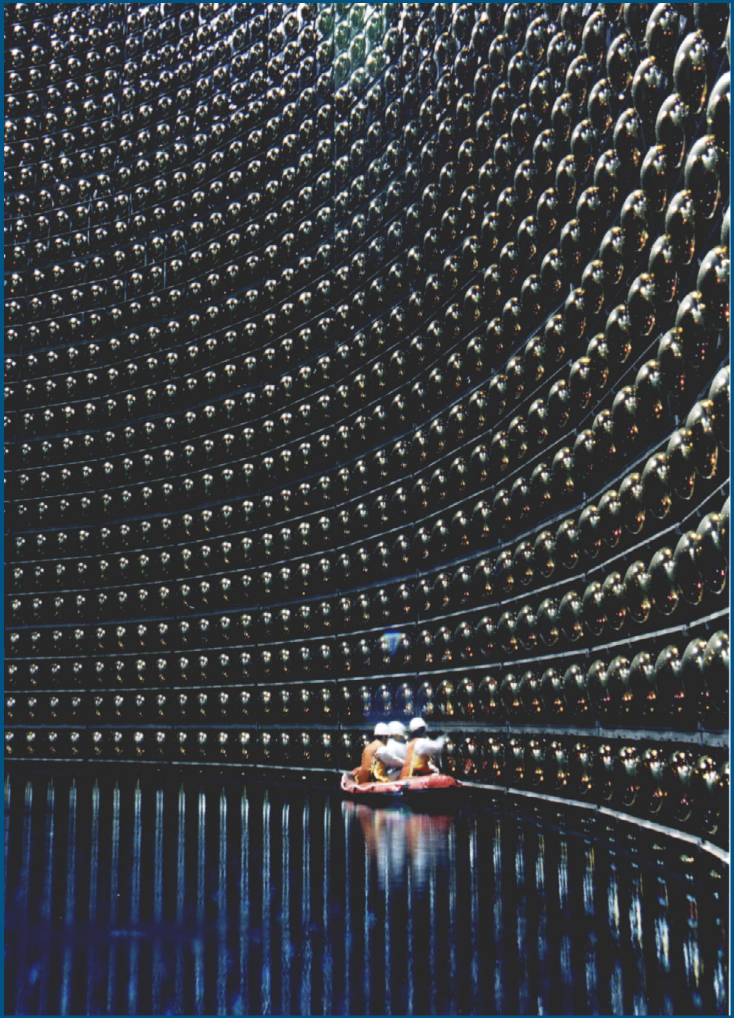
The first results were published in 2001 and the final in 2013, unambiguously showing that the total (electron+muon+tau) neutrino flux is in a good agreement with prediction, whereas the electron neutrino flux represent only ~1/3 of the total. That became a clear prove of explaining the solar neutrino problem by neutrino flavor oscillations.



Atmospheric Neutrino Oscillations

The compelling evidence in favor of neutrino oscillations was presented in 1998 by Super Kamiokande (50’000t water Cherenkov) detector.





SK oscillation results were later confirmed by the data of MACRO, Soudan, long- baseline experiments K2K, MINOS, T2K, NOνA, large neutrino telescopes ANTARES, IceCube. Appearance of tau-neutrinos was established on an event-by event basis by OPERA.

"For the greatest benefit to mankind"
Alfred Nobel

2015 NOBEL PRIZE IN PHYSICS

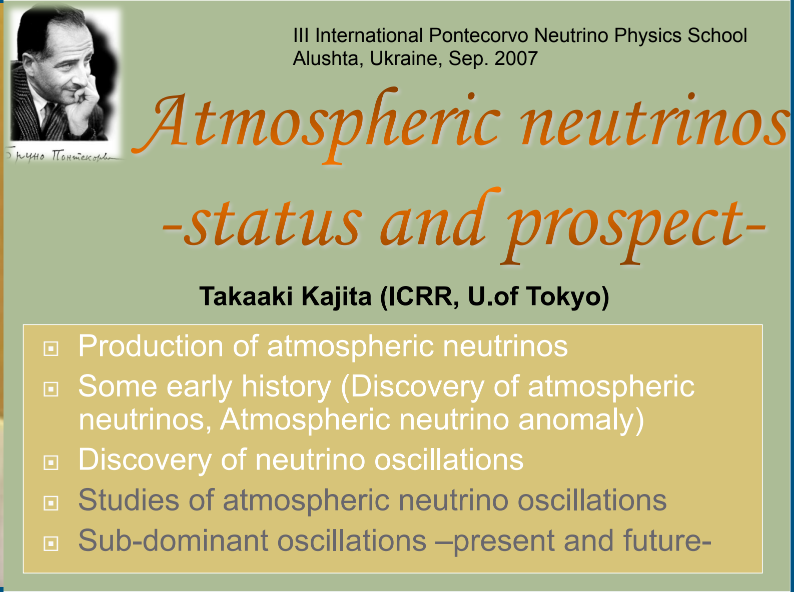
Takaaki Kajita
Arthur B. McDonald

Nobel Foundation. Photo: Lovisa Engblom.

for the discovery of ***neutrino oscillations****, which shows that neutrinos have mass*

2004. A.B.McDonald receiving B.Pontecorvo prize at Dubna.

2007. T.Kajita lecturing at B.Pontecorvo Neutrino Physics School organized by JINR.



III International Pontecorvo Neutrino Physics School
Alushta, Ukraine, Sep. 2007

Atmospheric neutrinos
-status and prospect-

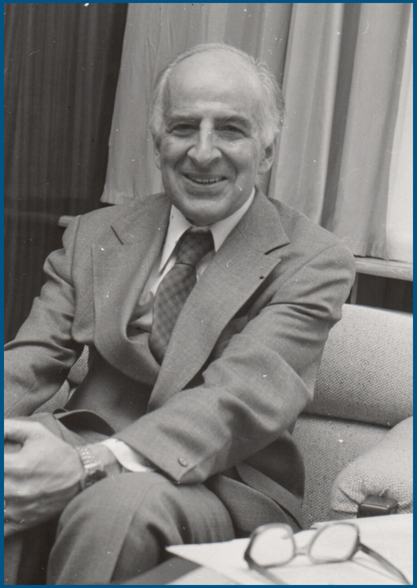
Takaaki Kajita (ICRR, U.of Tokyo)

- Production of atmospheric neutrinos
- Some early history (Discovery of atmospheric neutrinos, Atmospheric neutrino anomaly)
- Discovery of neutrino oscillations
- Studies of atmospheric neutrino oscillations
- Sub-dominant oscillations –present and future-

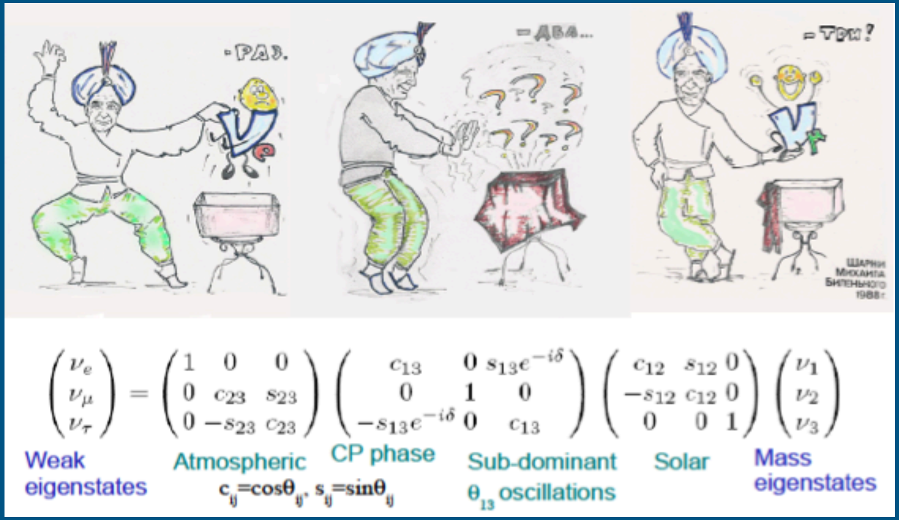
Undoubtedly, neutrino oscillations is the most outstanding idea of B.Pontecorvo.

He devoted many years to its development. It took significant efforts for the tiny neutrino masses to become reality.

The discovery of neutrino oscillations is the triumph of Bruno Pontecorvo's idea.



Now his name is eternized in the title of the neutrino mixing matrix – the Pontecorvo-Maki-Nakagawa-Sakata matrix.



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

$c_{ij}=\cos\theta_{ij}$, $s_{ij}=\sin\theta_{ij}$

Is it the end of the story?
And if not, why is it so important, what is the future?

The oscillation phenomena became an essential instrument for investigating neutrino. Precise measurements of oscillation parameters are required to answer the questions about unitarity of PMNS matrix, sterile neutrinos and the difference in quark and lepton mixings.

With the recent discovery of a non-zero θ_{13} mixing angle, the possibility to measure neutrino mass ordering and neutrino CP violation was opened. The latter is very important for understanding the baryonic asymmetry of the universe.

Another outstanding questions are the absolute mass scale, contribution of neutrinos to the dark matter, possible Majorana nature and other new physics, which may explain the smallness of neutrino mass.

Understanding the nature of neutrinos is of prime importance for elementary particle physics and also for astrophysics and cosmology.

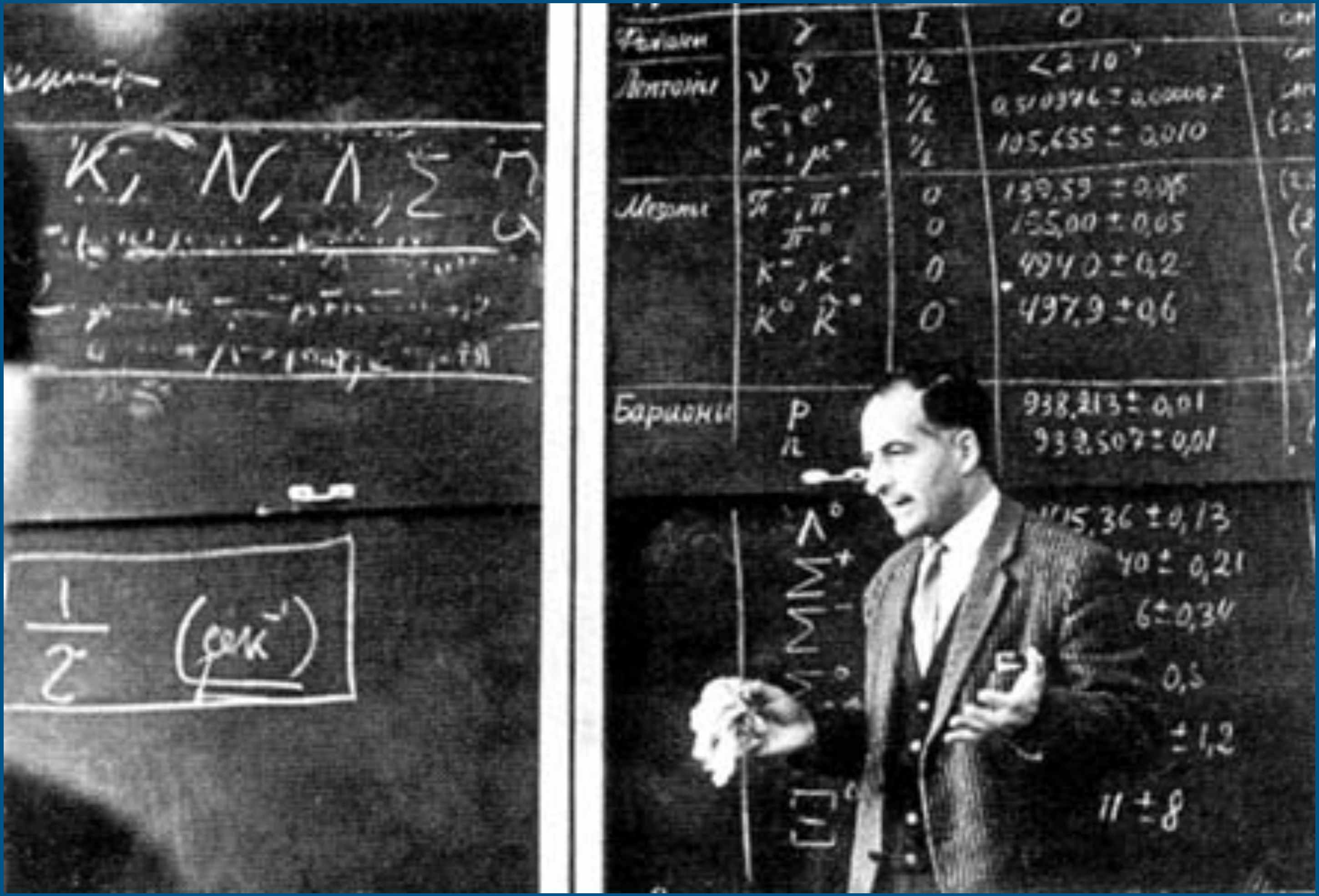
I think that Bruno Pontecorvo has understood an exceptional role of neutrinos long before this became clear to us.

The Neutrino Physics at JINR

- Precise measurement of oscillation parameters
- Measurement of mass ordering and CP violation
- Development of Neutrino detection technique
- Search for sterile neutrino states
- Search for neutrino-less double beta-decay
- Measurement of neutrino properties: mass, magnetic moment
- Neutrino astronomy
- Development of neutrino oscillations phenomenology
- Search for rare decays with LFV

An emphasis in this research is on experiments at JINR basic facilities at Kalinin Nuclear Power Plant, Baikal neutrino telescope and international projects with JINR essential contribution.

Dubna branch of Moscow State University



Bruno Pontecorvo was leading for 20 years the Chair of Elementary Particle Physics at Physics Department of Moscow State University

VI International Pontecorvo Neutrino Physics School

dedicated to the 60'th anniversary of JINR

August 27 - September 4, 2015

Horný Smokovec, Slovakia

WELCOME

The VI Pontecorvo neutrino physics school will be held in Grand Hotel Bellevue, on foot of the beautiful High Tatra Mountains, Slovakia within a period August 27 - September 4, 2015.

The program of the school will cover modern topics of neutrino physics including neutrino experiments, phenomenology and theory:

- Theory of neutrino mixing and masses
- Solar, atmospheric, reactor and geo neutrino experiments
- Direct neutrino mass measurements
- Neutrinoless double-beta decay
- Sterile neutrinos
- Dark matter
- Leptogenesis and Baryogenesis
- Neutrino cosmology and astronomy
- Statistics for nuclear and particle physics

The School is organized by

- Joint Institute for Nuclear Research (Dubna, Russia)
- Comenius University (Bratislava, Slovakia)
- Czech Technical University (Prague, Czech Republic)
- Charles University (Prague, Czech Republic)

In 1995 by the decision of the Scientific Council an International Prize was instituted at JINR in the memory of Bruno Pontecorvo.

The prize is awarded annually to an individual scientist and recognizes "the most significant investigations in elementary particle physics”.

Up to now, the Pontecorvo prize was awarded to 26 scientists from different countries and particle physics research areas.

2002. Samoil Bilenky is receiving the Pontecorvo prize for his theoretical investigations of neutrino oscillations.

The study of B.Pontecorvo at JINR is kept for visitors just as it was during his work there.

An EPS Historic Site was opened at Pontecorvo’s study at JINR on 22 February 2013

Bruno Pontecorvo has influenced significantly also the social life of the Dubna town. Dubna citizens remember this elegant man at concerts, exhibitions, playing tennis, underwater hunting and, especially, riding the bicycle.

A monument to Bruno Pontecorvo and Venedict Dzhelepov was opened at Dubna on 20 September 2013 on the occasion of centennial anniversaries of these two scientists and colleagues working together at JINR.

Conclusions

✓ There is a very rich scientific and cultural heritage of a great scientist and a man of the XXth century – Bruno Pontecorvo

✓ The discovery of neutrino oscillations is the triumph of his idea

✓ We are very proud that the scientific program of our Institute has been influenced by his outstanding talent, genius intuition and human personality

✓ In particular, the neutrino and astroparticle physics are among the flagship topics of the JINR program