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Colloquia: The Legacy of Bruno Pontecorvo

Neutrino physics and my debts to Bruno

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Summary. — After a brief introduction on the important role played by Bruno Pontecorvo in my scientific life, mainly involved in neutrino physics, I will shortly report the subjects where I could particularly appreciate his greatness which particularly impressed me. I will therefore consider in more details double beta decay especially in its neutrinoless channel were I was and am particularly involved, weak neutral currents, solar neutrinos, neutrino oscillation, determination of the neutrino mass and one unusual research of mine to which Bruno was particularly interested.

1. – Introduction

I first met Bruno Pontecorvo in an international conference in Kiev were I attended with considerable anxiety because I was very young. A the time I had proposed an experiment on double beta decay with a Germanium diode and carried out first measurements with this technique. I was incredibly flattered and honoured when the famous professor Pontecorvo asked of me to discuss the relationship of my results with the prediction of a new brilliant idea which he had just formulated. We started a discussion which became immediately quite animated because Bruno did the best he could to overcome my shyness which is normally unusual, but very strong in that case because of the presence of such an important physicist. This was always the same for the rest of his life during which I had the great honour of his friendship and the continuous theoretical —and not only theoretical— support of my activity in neutrino physics.

Bruno could not leave then the eastern countries, but we met many times in the Soviet Union and on the Balaton lake in Hungary for an international neutrino Workshops.

I apologize for giving in this talk some relevance to subjects in which I was involved in connection with Bruno. He was in all of them a source of inspiration and of indispensable advise.

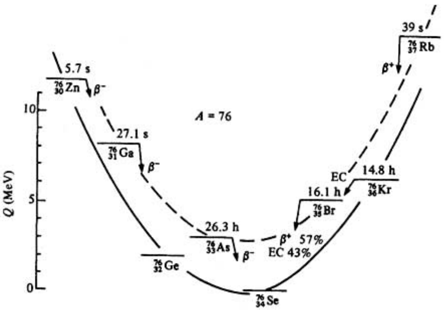

Fig. 1. – The $\beta\beta$ transition of ^{76}Ge.

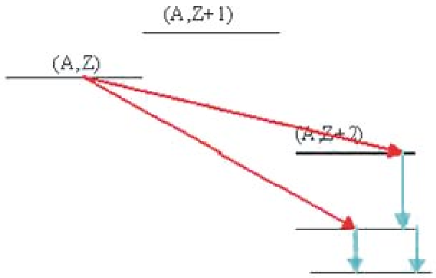

Fig. 2. – Double beta decay.

2. – Double beta decay

This fascinating process (fig. 1), suggested by the great physicist Maria Goeppert Maier in 1934, consists in the transition of the nucleus [A,Z] to its isobar [A,Z+2] and can be detected when the single beta decay to [A+1] is energetically forbidden or at least strongly hindered.

This transition can occur to ground or to excited states of the *granddaughter* nucleus (fig. 2)

At the time of the Kiev conference there were already many experiments on double beta decay, but only two were based on the principle of using a detector made of the same material which was also a source for this process.

The one by der Mateosian and Goldhaber was using a CaF_2 scintillator to detect the decay $^{48}\mathrm{Ca} \to {}^{48}\mathrm{Ti} + 2e^- + (2\bar{\nu}_e)$.

The one by Fiorini and collaborators was based on the decay $^{76}\mathrm{Ge} \to {}^{76}\mathrm{Xe}{+}2e^-{+}(2\bar{\nu}_e)$ on which many experiments are being carried out or planned today.

Double beta decay was not fashionable then, but Bruno was particularly interested in my experiment because he had a brilliant idea: that neutrinoless double beta decay was a direct $\Delta L = 2$ transition similar to $\Delta S = 2$.

Unfortunately this suggestion was not enforced by experimental results and I would like to report a comment by another great physicist Madam Wu who said:

"There are many experiments on double beta decay of poor quality, the only exception being that by Fiorini et al (wait a second!). The best however is the one by Wu and coworkers. As far as the suggestion by prof. Pontecorvo that neutrinoless double beta decay is a direct $\Delta L = 2$ transition, after the recent experimental results it lost part of its beauty".

Bruno said to me later: *"She was this time even too good with such a poor paper of mine!"*. I disagree because his idea was brilliant, but definitely not the best among the great ones of Bruno and not supported experimentally.

As it is well known double beta decay can occur in three channels:

1. $(A, Z) \to (A, Z + 2) + 2e^- + 2\bar{\nu}_e$,
2. $(A, Z) \to (A, Z + 2) + 2e^- + 1, 2...\chi$'s,
3. $(A, Z) \to (A, Z + 2) + 2e^-$.

Where χ is a massless Goldston boson.

TABLE I. – *Present results on neutrinoless DBD.*

Isotope	Technique	$\tau^{0\nu}_{1/2\,(y)}$	$<m_\nu>$ (eV)
^{48}Ca	CaF_2 scint	$>1.4\text{x}10^{22}$	<7-45
^{76}Ge (HM)	Ge diode	$>1.9\text{x}10^{25}$	<(0.3-1.27)
^{76}Ge (IGEX)	Ge diode	$>1.6\text{x}10^{25}$	<(0.33-1.35)
^{76}Ge (Klapdor 2004)	Ge diode	$1.2\text{x}10^{25}$	.38
^{76}Ge (Klapdor 2006)	Ge diode	$2.2\text{x}10^{2}$	.28
^{76}Ge (GERDA I)	Ge diode	$>2.1\text{x}10^{25}$	<(.29-1.1)
^{76}Ge (GERDA+HM+IGEX)	Ge diode	$>3\text{x}10^{25}$	<(.25-.98)
^{82}Se	Foil&track	$>.6\text{x}10^{23}$	<(0.89-2.)
^{96}Zr	Foil&track	$>9.2\text{x}10^{21}$	<(7.2-19.5)
^{100}Mo	Foil&track	$>1.1\text{x}10^{24}$	<(0.45-.93)
^{116}Cd	Scintillator	$>1.7\text{x}10^{23}$	<1.7
^{128}Te	Geochem	$>7.7\text{x}10^{24}$	<(1.1-1.35)
^{130}Te	Bolometer	$>2.8\text{x}10^{24}$	<(0.3-.7)
^{136}Xe	EXO	$>1.6\text{x}10^{25}$	<140-380
^{136}Xe	Kamland Zen	$>1.9\text{x}10^{25}$	<128-345
^{150}Nd	Foil TPC	$>1.8\text{x}10^{22}$	

The first process is the only one which preserves the lepton number and it has been detected in eleven nuclei, in some case also to excited levels. The most experimentally appealing is process 3, called neutrinoless double beta decay, rather improperly since also process 2 is neutrinoless. In neutrinoless double beta decay, since the recoiling energy of the nucleus is negligible, the two electrons share the total energy and in their sum energy spectrum a peak appears corresponding to the total transition energy.

Other possible $\Delta L = 2$ lepton violating processes like two positron decay, positron decay plus electron capture and two electron capture will not be considered here.

The present results are shown in table I together with the corresponding limits on the effective neutrino mass, where the uncertainties on transition nuclear matrix elements are considered.

It can be seen that the only evidence for neutrinoless double decay by of Klapdor *et al.* is in contrast with the results of Gerda I on the same nucleus both with the first paper and, being at 90 % confidence level, also with the second one. In an indirect way this is also true for the latest results on ^{136}Xe.

3. – Discovery of weak neutral currents

Around the end of the sixties I was involved in searches on neutrino physics with bubble chambers. Our friend, the late Carlo Franzinetti, suggested to the Italian Institute for Nuclear Physics (INFN) the construction of a massive bubble chamber with heavy liquid as a competitor to hydrogen bubble chambers for the easier construction and lower price. The Institute was very favourable, but the project could not be realized in Italy due to lack of funds. Fortunately another great physicist and friend, Andre Lagarrigue, was able to construct the famous chamber Gargamelle and generously accepted the participation of my country under my direction already during construction.

The participation of the Italian group included also Carlo, also an admired of Andre. Lagarrigue. Gargamelle gave fundamental results in neutrino physics, but in the first collaboration meeting which took place in Milan weak nuclear currents were not the first in the list.

Even Franzinetti after an animated discussion wrote on my blackboard *"... le correnti neutre le lascio a Fiorini"* (I leave neutral currents to Fiorini) (fig. 3).

It was Bruno who, convinced of their importance, supported me in the neutrino-72 meeting in Balatonfured, together with other collegues, like Antonino Pullia.

Fig. 3. – Arguments between Carlo and Bruno (credit: JINR, Dubna).

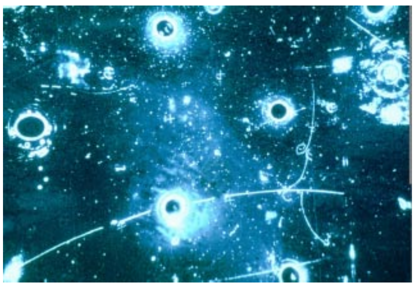

Fig. 4. – July 1973: Gargamelle first neutral current (credit: CERN Archives).

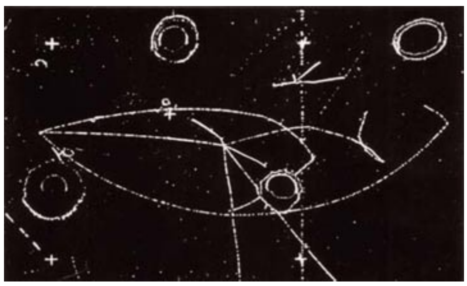

Fig. 5. – A hadronic neutral current.

As usual Bruno was right and in 1973 we proved the existence of neutral currents both in leptonic and hadronic neutrino interactions (fig. 4 and 5)

4. – Solar neutrinos

This is definitely the subject where the extraordinary genius of Bruno Pontecorvo reached the maximum accomplishment for the future of neutrino physics. As an experimentalist I particularly liked that in the famous Canadian internal report about revealing the neutrino, in suggesting the best detector, he was even considering the cost of the target material which is still now one of the more serious problem due to the large needed mass. My activity was closely connected with his suggestions inducing me and my group to join the European GALLEX collaboration for a radiochemical experiment with Gallium in the Laboratori Nazionali del Gran Sasso.

Figures 6 to 9 show the spectrum of solar neutrinos, an animated discussion with Nino Zichichi and Till Kirsten, GALLEX and the GALLEX Collaboration.

In the Neutrino Conference in Spain Bruno was there sitting in the front row and I was chairing the session. After the report on the detection by GALLEX of the pp neutrinos by Till Kirsten, Bruno wanted to say something, but was prevented by the Parkinson disease which severely affected him. I translated his congratulation to the audience and to Till who bowed to him simply saying: *"Professor Pontecorvo we were indebted of this to you"*.

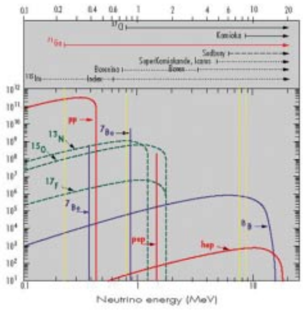

Fig. 6. – Spectrum of solar neutrinos.

Fig. 7. – Discussion with Nino Zichichi (credit: E. Fiorini and Collaborators).

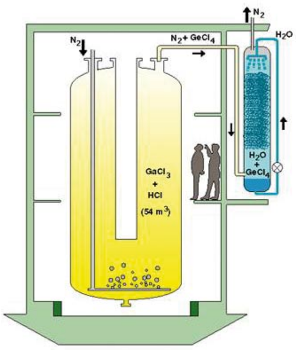

Fig. 8. – The GALLEX detector (credit: GALLEX Collaboration).

Fig. 9. – The GALLEX Collaboration.

Even if there were hints of oscillations by the first solar neutrino experiments, Bruno Pontecorvo could not enjoy the success of his prediction of oscillations in the repeated experiments on solar and atmospheric neutrinos, followed by beautiful experiments on neutrinos with accelerators and reactors (fig. 10).

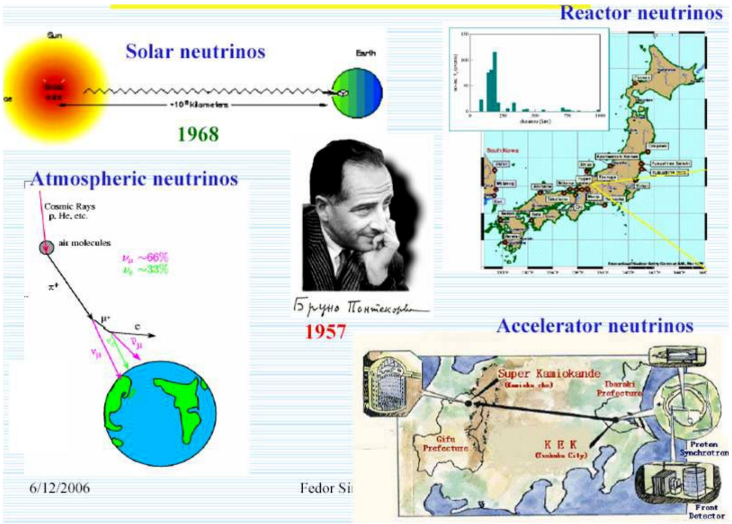

Fig. 10. – Bruno and neutrino oscillations.

In the correponding equation only one of the mixing angles (θ_{13}) was missing up to one year ago. Recently however, after indications by Double Chooz and accelerator in Japan, two measurements in Reno (South Corea) and Daya Bay (China) reported respectively:

$$\sin^2\theta_{13} = 0.092 \pm 0.016(stat) \pm 0.005(syst),$$
$$\sin^2\theta_{13} = 0.103 \pm 0.013(stat) \pm 0.011(syst).$$

What a pity that Bruno is not with us to celebrate this extraordinary result of the oscillation theory!

Oscillation experiments have proved unambiguously the non zero value of the difference between the squares of the mass of two neutrinos of different flavours... As a consequence we know that the neutrino mass is finite even if we are unable to determine its value. This is today one the most challenging adventure even outside elementary particle physics.

Neutrino mass can be determined in three ways: cosmology and single and double beta decay (fig. 11).

Cosmological methods (fig. 12) have reached a sensitivity on the sum of the neutrino masses of the order of a tenth of eV. This is however in some way model dependent.

Single beta decay (fig. 13) is in principle the only model independent method since it is based on the deformation of the beta spectrum due to the mass of the neutrino (fig. 14). The present limit of $\sim 2\,\mathrm{eV}$ is going to be improved by an order of magnitude by the international KATRIN experiment.

5. – The second mystery of Ettore Majorana

A very important event in 1979 for all of us and also for Italian physics was the unexpected first visit to our country by Bruno (figs. 15 and 16).

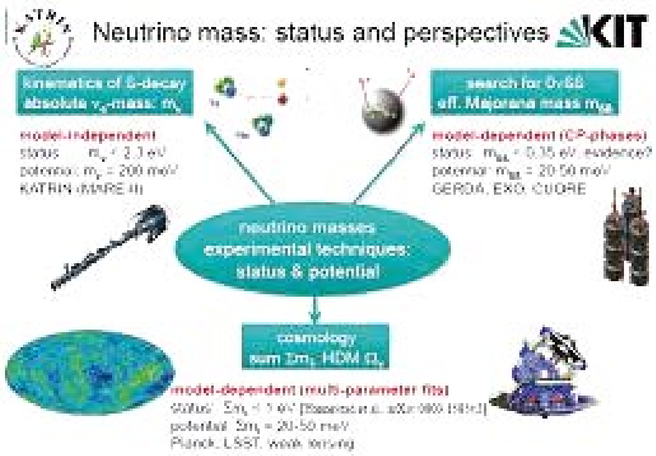

Fig. 11. – The three ways to determine the neutrino mass.

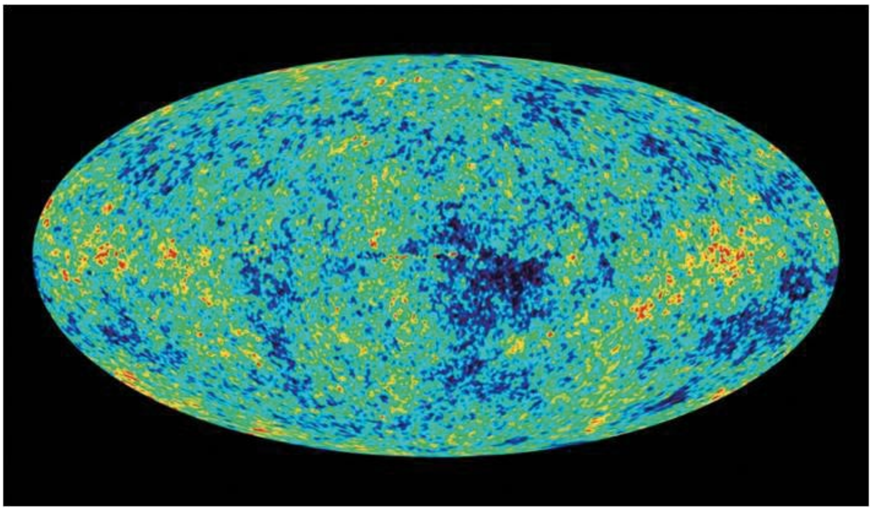

Fig. 12. – Cosmology (credit: NASA Archives).

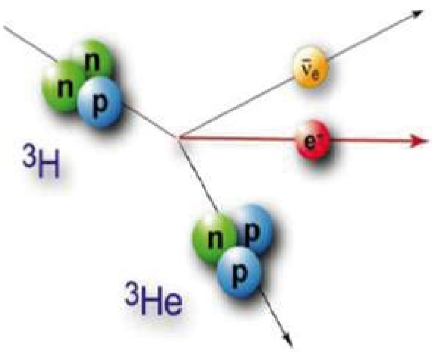

Fig. 13. – Beta decay of tritium.

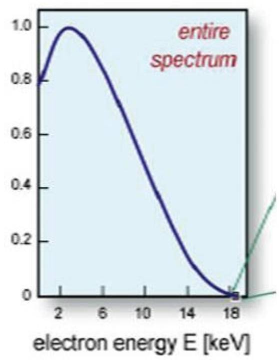

Fig. 14. – The beta spectrum.

Fig. 15. – With Bruno in Rome in 1978, during his first visit to Italy on the occasion of Edoardo Amaldi's 70th birthday (credit: Amaldi Archive, Department of Physics, Spienza University, Rome).

Fig. 16. – With Gilberto Bernardini (credit: Amaldi Archive, Department of Physics, Sapienza University, Rome).

Only one year after I had the great pleasure to have Bruno in Neutrino-1980 which I had organized in Erice under the generous hospitality of Nino Zichichi.

Starting from then and in the numerous following visits of Bruno in Italy and even in Milan the presence and advice of Bruno was fundamental for me in the main search on which I was and am involved: neutrinoless double beta decay.

My present activity, strongly related to Bruno, aims to understand the neutrino nature: is it a lepton conserving Dirac particle or a lepton violating Majorana particle as suggested by another great Italian physicist Ettore Majorana just one year before his mysterious disappearance?

The existence of neutrinoless double beta decay would be the only way to solve this mystery since it would indicate the violation of the lepton number. If existing neutrinoless double beta decay could also allow to determine, even if indirectly, the neutrino mass.

Stimulated by this exciting question many second generation double beta decay are planned, as indicated in table II.

Table II. – *Second generation experiments and plans on neutrinoless DBD.*

Experiment	Isotope	Mass	Technique	Present Status	Location
AMoRE[89,90]	^{100}Mo	50 kg	$CaMoO_4$ scint. bolometer crystals	Development	Yangyang
CANDLES[91]	^{48}Ca	0.35 kg	CaF_2 scint. crystals	Prototype	Kamioka
CARVEL[92]	^{48}Ca	1 ton	CaF_2 scint. crystals	Development	Solotvina
COBRA[93]	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CUORE-0[69]	^{130}Te	11 kg	TeO_2 bolometers	Construction - 2012	Gran Sasso
CUORE[69]	^{130}Te	203 kg	TeO_2 bolometers	Construction - 2013	Gran Sasso
DCBA[94]	^{150}Ne	20 kg	^{enr}Nd foils and tracking	Development	Kamioka
EXO-200[57]	^{136}Xe	160 kg	Liq. ^{enr}Xe TPC/scint.	Operating - 2011	WIPP
EXO[70]	^{136}Xe	1-10 t	Liq. ^{enr}Xe TPC/scint.	Proposal	SURF
GERDA[71]	^{76}Ge	≈35 kg	^{enr}Ge semicond. det.	Operating - 2011	Gran Sasso
GSO[95]	^{160}Gd	2 ton	Gd_2SiO_5:Ce crys. scint. in liq. scint.	Development	
KamLAND-Zen[96]	^{136}Xe	400 kg	^{enr}Xe disolved in liq. scint.	Operating - 2011	Kamioka
LUCIFER[97,98]	^{82}Se	18 kg	ZnSe scint. bolometer crystals	Development	Gran Sasso
MAJORANA[77,78,79]	^{76}Ge	26 kg	^{enr}Ge semicond. det.	Construction - 2013	SURF
MOON [99]	^{100}Mo	1 t	^{enr}Mofoils/scint.	Development	
SuperNEMO-Dem[87]	^{82}Se	7 kg	^{enr}Se foils/tracking	Construction - 2014	Fréjus
SuperNEMO[87]	^{82}Se	100 kg	^{enr}Se foils/tracking	Proposal - 2019	Fréjus
NEXT [82,83]	^{136}Xe	100 kg	gas TPC	Development - 2014	Canfranc
SNO+[84,85]	^{150}Nd	55 kg	Nd loaded liq. scint.	Construction - 2013	SNOLab

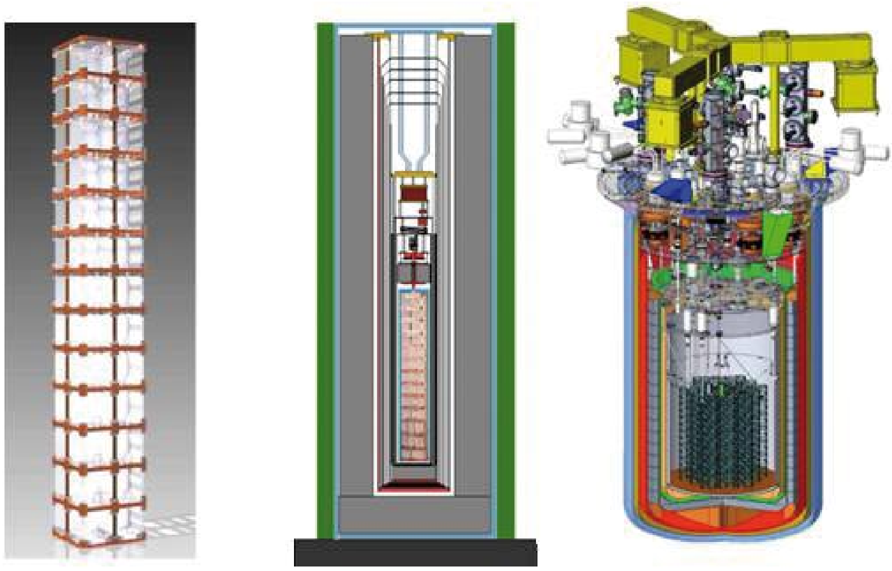

Fig. 17. – CUORICINO, CUORE0, CUORE.

At present CUORE (for Cryogenic Underground Observatory for Rare events) which is near completion in the Laboratori Nazionali del Sasso is the only Cryogenic massive second generation. It is based on the search for the decay

$$^{130}\mathrm{Te} \to {}^{130}\mathrm{Xe} + 2e^{-} + (2\bar{\nu}_e),$$

where ^{130}Te has an isotopic abundance of 34% and a transition energy of 2347 keV. Four massive arrays were or are being constructed:

- MIBETA (Milan) an array of 20 bolometers of $TeO_2 \to 6.8$ kg;
- CUORICINO (CUORICINO Coll.) 62 Bolometers of $TeO_2 \to 40.7$ kg;
- CUORE0 a test array practically identical to one column of CUORE, in operation;
- CUORE (CUORE collaboration) 988 crystals of $TeO_2 \to 741$ kg, proposed in 1998 and presently in construction.

The development the last three of these arrays is shown in fig. 17. CUORE0 is presently successfully taking data and CUORE is near to completion.

6. – The problem of the Roman lead

Bruno was a great physicist with multidisciplinary interests. For this reason I dare to report here on an unusual activity of mine on which he was much interested at the level to assist to conferences of mine at the LNGS and at Accademia Nazionale dei Lincei of which he was a foreign member.

Lead is in principle an excellent shielding material for experiments on rare events due to his high atomic number, reasonable mechanical properties and accessible cost. Unfortunately this metal contains ^{210}Pb which decays with an half lifetime of 22.6 years. As a consequence only ancient lead is free from ^{210}Pb radioactivity.

The discovery of a Roman ship transporting lead sunk near the coast of Sardinia prompted me to investigate the properties of this lead and to try to obtain a large quantity of it to shield our experiment on rare events in the Laboratori Nazionali del Gran Sasso. This *"navis oneraria magna"* was transporting about two thousand lead ingots of 32 kg each. INFN funded the recovery of one thousand of them (the other were spread out inside the sand) (fig. 18).

About three hundred of these ingots where given to us to be used for our experiments under condition of saving the beautiful inscriptions on the top of each ingot (fig. 19).

Fig. 18. – Recovery of the lead ingots (credit: E. Fiorini and Collaborators).

Fig. 19. – Inscription on one of the ingots (credit: E. Fiorini and Collaborators).

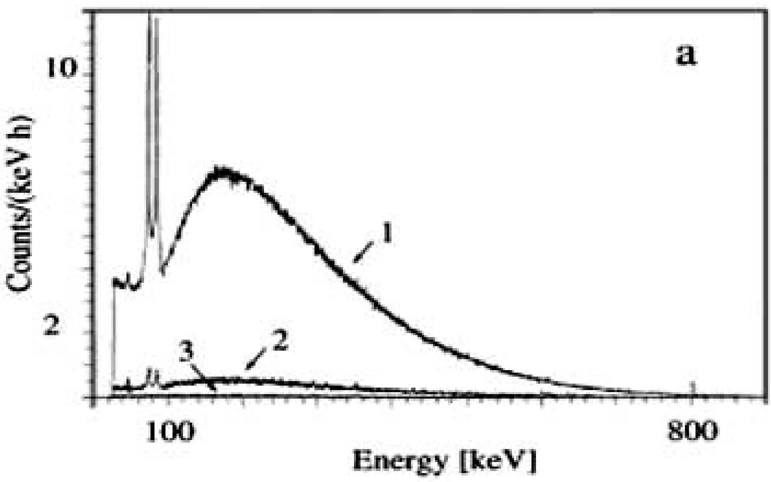

Fig. 20. – Spectra from various sample of lead: 1. Modern Lead; 2. Commercial Low Radioactivity Lead; 3 Roman Lead.

The radioactivity spectrum of Roman lead is compared in fig. 20 with those of modern lead and of industrial lead specially produced to ensure low radioactivity. The spectrum of Roman lead cannot be distinguished from the abscissa line.

With high sensitivity measurements carried out with bolometers we were able to set a 90% c.l. limit of 4 mBq/kg for Roman lead, the lowest existing for this metal.

7. – Conclusions

This report presented as an inadequate tribute to Bruno Pontecorvo cannot end with a standard conclusion. While writing it I could realize how much I owe to this man who was so great not only from the scientific, but also from the human point of view.

His contributions to our science and in particular to neutrino physics all over his life is unforgettable. Due to our different ages I could not follow directly his great impact in physics before, during and immediately after the war. Since however I met him fequently in Russia and later in Italy and in other countries I had the great privilege of learning so much from him. Since he also honoured me with his friendship in so many occasions I dare to report two episodes that show the humanity in the country where he choose to spend the last part of his life.

The first episode where he was not present, but which he much liked when I reported to him, took place when I was In Protvino (Serpukov) to investigate on behalf of INFN a possible bubble chamber experiment there. Tired by the work I was walking in the country and passed near an hut where a farmer said hallo to me. We started a totally useless conversation since we did not know a single word of one another speech, but the farmer entered in his hut and gave me as a gift an enormous cabbage. I did not refuse it, as I was afraid of offending him but one can imaging my difficulty to offer it and have it cooked in the canteen of our hostel!

I have a particular unforgettable recollection of one time I was invited by the Academy the Soviet Union for a neutrino conference which took place in a village in the beautiful

Elbrus mountain. While the foreign members of the Conference were located in a beautiful Hotel where also the Conference took place, I was housed in a much more modest *House of the Pioneers*. Life there was very pleasant and strange: I was sleeping alone in a big room with six beds and the food was good, but arrived in a somewhat irregular way. We received steaks and beer for breakfast and fruit for lunch. Once I asked the maid a coffee, one of the few Russian words I knew, and she disappeared for a quarter of an hour. When she returned with the coffee I realized that she had prepared that in her house!

All people there knew only Russian, but that was no problem for me because Bruno spoke with me in Italian introducing me as *tovarich Fiorini*. I remember that each morning Bruno and myself had a rather long walk to the Conference in a beautiful landscape talking in Italian on physics. As I told once to Gillo, Bruno's brother, this was the best week of my life.

I still remember when in Milano I received the following mail by Samoil Bilenki:

"Dear Ettore, Bruno died yesterday night by pneumonia in the Dubna Hospital. It is a great loss for our science and his friends. I worked with him for 20 years and thank God for that".

Since Bruno was born in Italy, but died in Russia I would like to repeat a sentence by Puskin's teacher:

Of companions of our life, when they leave us, we should not say with sorrow "They left us", but with gratitude "They were".