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# Particle detectors and society

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You may find the title of the talk intriguing, namely "Particle Detectors and Society". It looks a little bit like "Arsenic and old lace". Until you have seen the film you cannot see what is the connexion between the two parts. I was given this title and since then I have been inclined to try to deliver what the organizers wanted to listen to.

I discovered CERN in the year 1959, when I was at a conference on high-energy physics in Venice. I was a low energy nuclear physicist, working at the Joliot-Curie Laboratory at the Collège de France.

Two sessions at the Summer school of theoretical physics at Les Houches, organised by Cecile Morette, plus friendly contact with colleagues working at Leprince-Ringuet's Laboratory at the Ecole Polytechnique, had convinced me that particle physics was the most exciting field.

I tried to go to Dubna, during the first timid exchanges of scientists between France and the Soviet Union, but for reasons unknown to me I never received the visa I was promised.

The conference in Venice opened the door to a promised land for me. It was there that Donald Glaser presented the first results obtained with the bubble chamber he invented a few years earlier. To validate my candidacy at such a conference I presented a quite novel gaseous detector, with intriguing properties, which however did not arouse anybody's interest, led to no experiment, but was of great importance to me.

Leon Lederman came to me after the talk. He was going to visit CERN on a sabbatical year, with the goal of investigating ways to measure the anomalous magnetic moment of the muon. He was looking for slave labour and after my talk had the illusion that I had some of the skills he needed for the young European team he had to assemble. It was one of the most ambitious experiments planned with the new accelerator, which had been built at CERN.

He offered me a fellowship for one year and I spent thirty years there. I was hired at the age of 35, after my PhD, which means that I was not a beginner. The laboratory of Joliot-Curie had some excellent features. The lectures by Joliot, on the history of nuclear physics, were inspiring. The laboratory was empty as far as modern equipment was concerned and most of the young emerging physicists were clever at experimental physics and had to build their own instruments. So I started to build 130 Geiger Counters of which only 20% deigned to work properly, despite my respect for written recipes.

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At that time we were competing with Martin Deutsch of MIT, on a problem on angular correlation between two gamma rays emitted by a nucleus. He was using scintillation crystals and photomultipliers, freshly available in the USA.

It was thus hopeless to try to compete and for my thesis I started with a slightly elder colleague, F. Suzor, the construction of an instrument consisting of two large single wire proportional counters, tangential along a plane, which permitted us to study the correlation between very low energy electrons, starting practically from zero energy, and $\beta$-rays in coincidence.

There is not much point in describing our results and I only want to mention that I learned everything there was to be known about negative pulses, positive pulses, the timing of the pulses produced by an avalanche in single wire proportional counters and later it proved to be a real treasure when I entered the field of multiwire proportional chambers, in 1967.

I later invented the gaseous detector which was a pretext to go to Venice in 1959. I joined CERN in 1960 and worked for three years on the measurement of the anomalous magnetic moment of the muon. It was a great time because the experiment was difficult, requiring many innovations in the instrumentation and because the group of physicists who jointly ran it were enthusiastic, hard working and talented. For one year we also enjoyed the leadership of R.L. Garwin, who spent a sabbatical year at CERN and who was an artist and a living encyclopaedia, as far as experimental physics is concerned.

After the success of the first stage of the experiment it appeared that there were ways to considerably improve the accuracy and a fraction of the team continued for decades with new actors led by Francis Farley and Emilio Picasso while others decided to change subjects and I was among them. The ambiance at CERN was very stimulating. All the experimental physicists there aimed to understand the theoretical grounds of their experiences and were eager to follow courses on theoretical physics. I remember that often at the end of a night shift, when there was an academic lecture at 11:00 a.m. we slept for two hours in our offices and then went to those lectures.

It was a time when the new accelerators and the new interrogations in physics were demanding new detectors capable of giving a more precise spatial accuracy than the scintillating counters. They had to be as fast, and deliver spatial information on the coordinates of the large number of particles produced simultaneously in a collision, well enough to permit identification of rare and complex events. I went back to detectors and introduced two new types of automatic spark chambers. It was a golden age. If you showed that you had an idea you could hire three technicians for your group, a young experimentalist, a couple of visiting experimental scientists from the Unites States.

In 1967, at the same time as probably half a dozen other teams I decided that it was worth making use of the proportional mode of amplification existing in proportional wire chambers. The experience I had acquired during the years working with single wire proportional counters was extremely useful. The first chambers of $10 \times 10$ cm$^2$ with wires spaced at a distance of 2 mm, worked like a charm and since we understood the origin of all the phenomena we were observing it led us immediately to the one dimensional wire chambers, 1000 times faster than a spark chamber, then to the two dimensional wire chambers, essential for the localisation of X-rays and to the drift chambers which became an essential instrument in some experiments requiring large surface with accuracies of the order of 100 microns.

I must say that making these detectors, gave me the opportunity to collaborate with very talented and clever young physicists who came to CERN to work on new detectors for varying lengths of time and this developed my taste for this activity. I would have to mention a good dozen or so names to do justice to all the visitors who made original contributions. It led us to some very useful developments, like the multistep avalanche chambers and the light emitting proportional chambers. Some of our collaborators are now leaders of reputed groups in detector physics in Israel, at CERN, in the USA and Europe.

I personally invested much of my time and energy in the X-ray imaging for biology application and had the pleasure of equipping the Synchrotron Radiation Facility at Orsay with an imaging spherical drift chamber, which for 10 years was a major tool for studying the structure of large molecules. I mention it because this project was simply presented under the umbrella of being a test bench for the study of two dimensional high accuracy localisation of a low energy X-ray, which it was indeed! But I am not sure that at the present time at CERN, or elsewhere, such freedom would be encouraged, except in some wealthy university laboratories.

I continued to work on detectors when the LHC came with dramatic requirements for new detectors, capable of surviving the much higher rates and handling much higher multiplicities.

With my friend Ioannis Giomataris, we started to work on a new gaseous detector, "Micromegas", while other groups fought to impose different gaseous detectors. We all lost the battle against the solid state detectors. When I see the results obtained now by the groups in Saclay which have developed Micromegas to a level where it can easily match the characteristics required for LHC physics, at a lower cost and when I also look at the characteristics of "GEM", the gaseous detector developed by Fabio Sauli's group, I think that giving up the gaseous detector too hastily was of questionable wisdom since the choice of solid state detectors has been probably a source of considerable increase in expenditure.

Before this talk Giomataris sent me fifty pictures illustrating what is being undertaken now with Micromegas and I was impressed by the ambitious programmes of research in high-energy physics, now undertaken with this detector. It would take two hours to present all the pictures and one week for me to understand their content. So I will limit myself to a few slides.

The principle of the detector is shown in Fig. 1. They have now reached an intrinsic time resolution of 0.2 nanosecond (Table 1), the intrinsic position resolution is three to four microns, the reason why you don't reach it when you make an experiment with particles is due to a

**Table 1.** Performances of Micromegas obtained in various particle beams with Minimum Ionising Particles. The 0.2 ns time resolution has been obtained with a UV pulsed laser creating single photoelectrons on the micromesh

| | |
|---|---|
| Spatial resolution | 12 µm (rms) with MIPs |
| Time resolution | 0.2 ns (rms); 0.7 ns with MIPs |
| Energy resolution | 11.8% (5.9 keV) (FWHM) |
| Gas gain | $\gg 10^4$ |
| Counting rate | $\gg 10^6$/mm$^2$/s |
| High radiation resistance | |

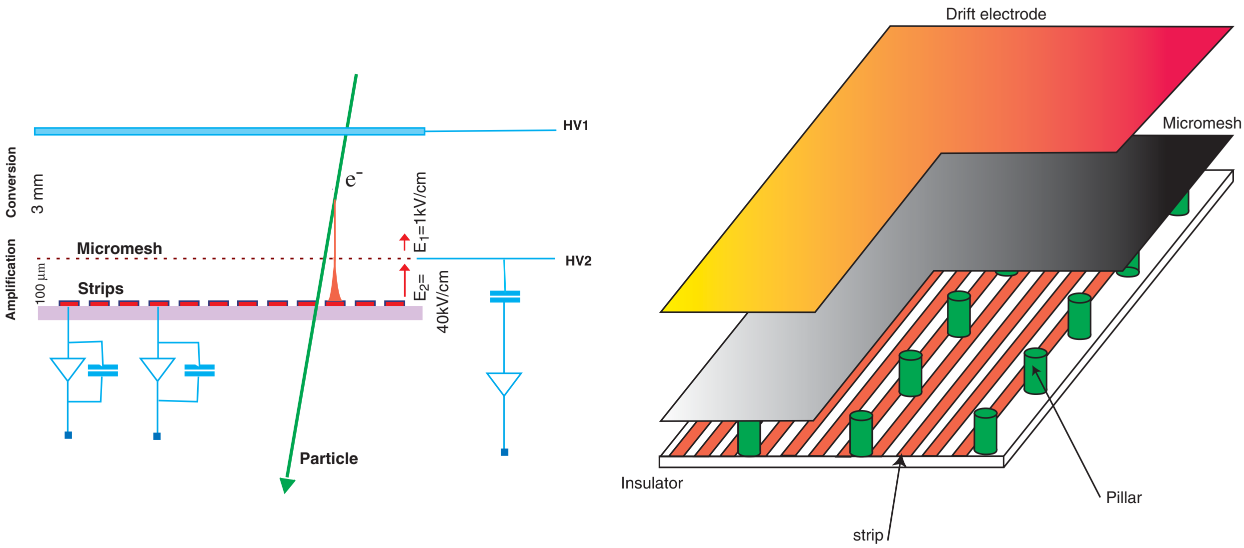


**Fig. 1.** Micromegas principle [1]: a high field region is formed between the micromesh and the readout strips with the help of 100 µm? high pillars etched on the micromesh. The amplification process occurs in the small amplification gap leading to a fast elimination of the positive ions

jitter introduced by the position of the initial electron. The Saclay group is now running an experiment in which they have, over one square centimetre (Fig. 2), $10^8$ particles per second and with a time resolution of 0.7 nanosecond. In another experiment, COMPASS, they have been running for two years with twelve chambers, without any problems and have reached seventy-micron accuracy with 9 nanosecond resolution (Fig. 3). If we had had these 40 by 40 cm prototypes four years ago, I think we would have had an influence on the detector chosen for the LHC. But it is not very important since ambitious experiments are undertaken anyhow, because of the unmatched intrinsic advantages of gaseous detectors.

Physicists want to search for the axions produced in the Sun, coming massively to the Earth, and detect them by interaction with a magnetic field produced by the magnets of the LHC. Soft X-rays (1 to 8 keV) are produced and detected with 100% efficiency since the noise of the detector is very small. They dream that in a few months they may see the axion.

Detectors are now being used or developed for neutron tomography, X-rays imaging. Another experiment projected by Giomataris and his group relies on a source of tritium, which is equivalent to what you need for a thousand thermo-nuclear bombs. It is a very intense source of neutrinos. With a small detector Micromegas outside the source and a drift length of 10 meters, whenever you have a reaction produced by an elastic scattering of the neutrinos with electrons, the ionisation electrons moving back will give you a good position and time resolution to have all the ion pairs detected individually (Fig. 4). The information allows you to see if you have oscillations or not. The maximum oscillation occurs at 6.5 meters. It is a nice dream to compete with people who are doing this type of research with accelerators, where they detect the neutrinos at a distance from the target of 730 kilometres with an event rate a million times smaller. The difficulty indeed is to put your hands on so much tritium, which exists and is useless. They expect ten thousand events per

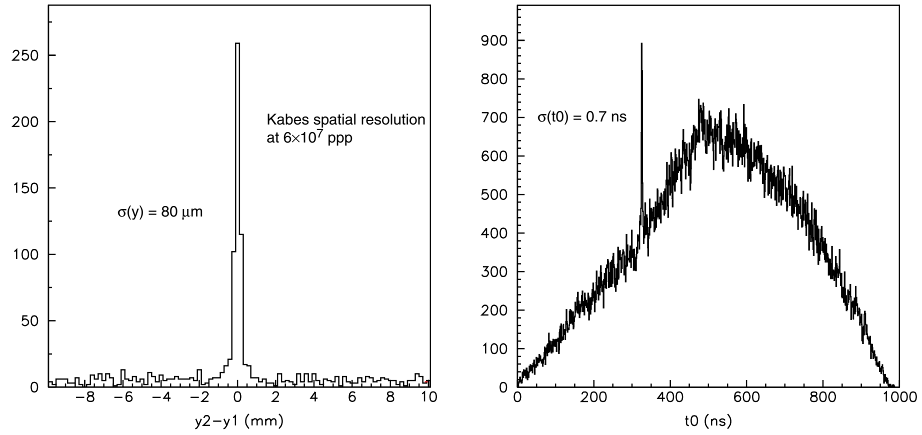
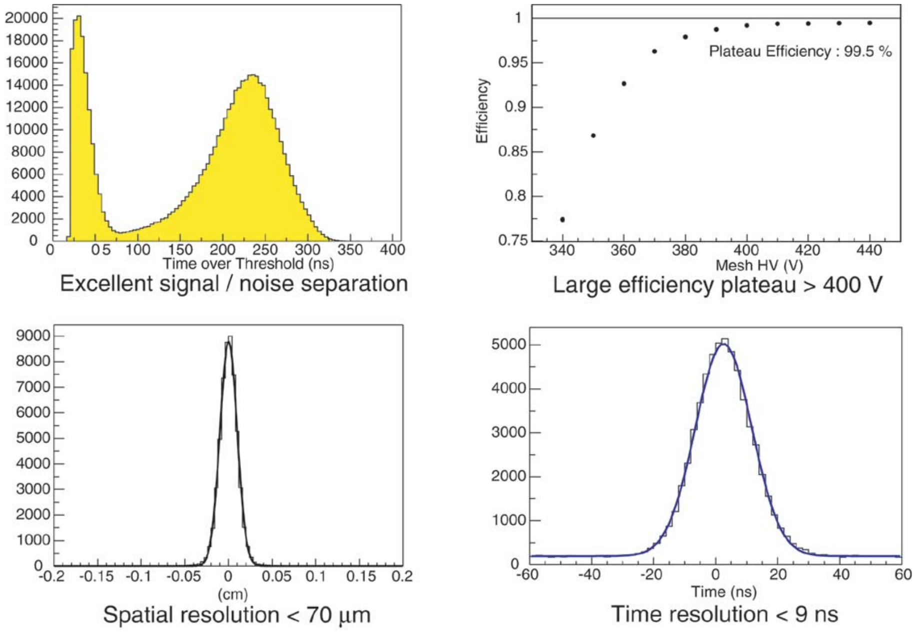


**Fig. 2.** The performance of the Kabes mini-TPC read-out by the Micromegas detector at very-high rates. The detector had a successful run inside the kaon beam of the NA48/2 experiment [2]



Excellent signal / noise separation

Large efficiency plateau > 400 V

Spatial resolution < 70 μm

Time resolution < 9 ns

**Fig. 3.** Performance of the COMPASS Micromegas detectors [3], the largest chambers build with the novel micro-pattern technology, running since 3 years in a stable fashion

year if they can reach 10 bar pressure. Being high-energy physicists, they are afraid of nothing.

I think I was not bold enough to stay in high-energy physics and I decided a long time ago to work on applications in medicine and biology. I will show a few images that illustrate my activity. Figures 5a, 5b and 5c show various quantitative images of the distribution of pharmaceutical molecules with different radio elements in animal sections. They were obtained with the $\beta$-imager, which I have developed, or with the $\mu$-imager, which has also been derived by an Orsay Group from Particle Detector Physics. The $\beta$-imagers are a direct fall-out of high-energy physics, when we were taking the image of the avalanches with image intensifiers. In 20 minutes we obtain images, which required one month with a film, making such studies impossible. Because of the different response of the detector for different energies, it is possible to separate the signals from two different isotopes (Fig. 6). I have had the pleasure of seeing biologists from large pharmaceutical laboratories coming to us, with a sample, labelled with long-lived isotopes. They were invited to a good meal, and when they came back they had an image that they could obtain in one month with traditional methods. That is the reason why about a hundred of these instruments are now used in biology research. Some biologists might make discoveries, which they could not have made without this instrument and this is an illustration of the contributions which big laboratories like CERN can make in fields of major importance. We already have the Web, which is a big thing. Here we have something less visible which may become important.

Now I come to radiology. A Russian group from Novosibirsk made a wonderful study on radiology of human beings with wire chambers. Figure 7 shows the results we are now obtaining. The images are taken from two orthogonal directions and we have learnt how to use an algorithm, which allows a 3-D reconstruction of bones. You see the details in projection, where the resolution is approximately 250 μm. The dynamic range is 30’000. It is in use in a hospital for children in Paris, where they treat scholiotic children. The advantage with respect to

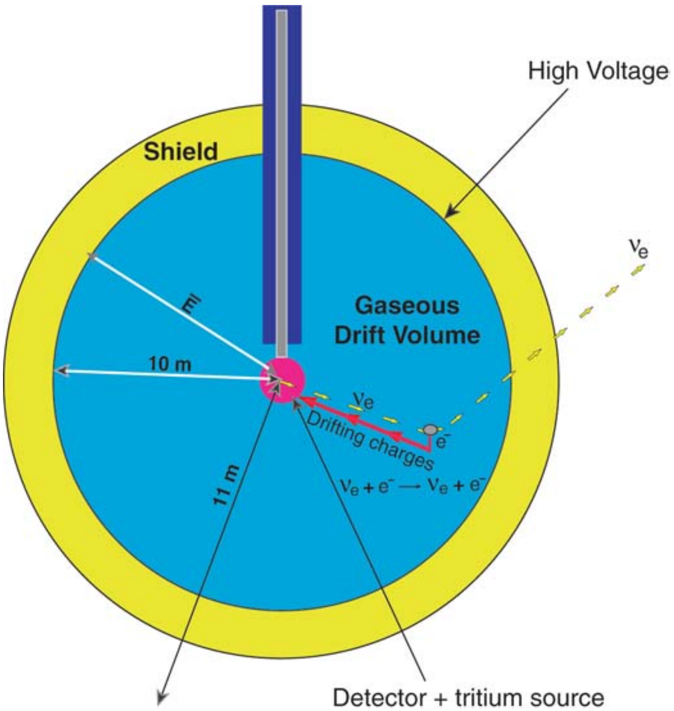


**Fig. 4.** NOSTOS: a new proposal [4] to measure neutrino oscillations using an intense tritium source as low-energy neutrino beam. The idea is to use radial drift chamber geometry with the Micromegas detector surrounding the neutrino source at a distance of 50 cm from the centre. Electron recoils produced in the gaseous drift volume (10 meter in radius) are creating ion pairs that are collected and amplified by the Micromegas detector

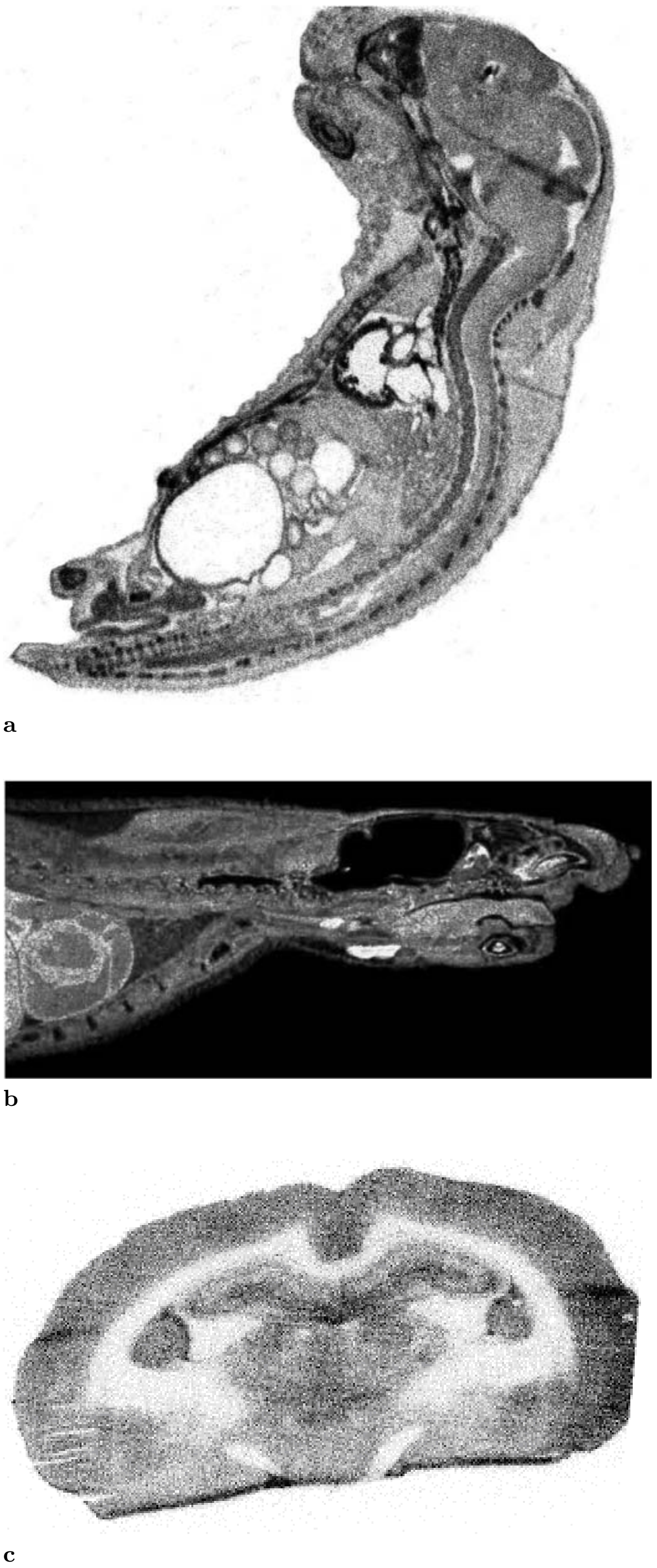


**Fig. 5.** **a** μ-imager picture of receptor binding of a $^{125}$I compound in a mouse embryo (15 μm resolution) [5]. **b** $\beta$-imager picture of $^{3}$H labelled whole body rat sections acquisition [6]. **c** $\beta$-imager picture of a rabbit brain: $^{99}$Tc labelled HMPAO complex accumulation in the cortex, the thalamus, the hippocampus. (Spatial resolution for $^{99}$Tc is 50 μm) [7]

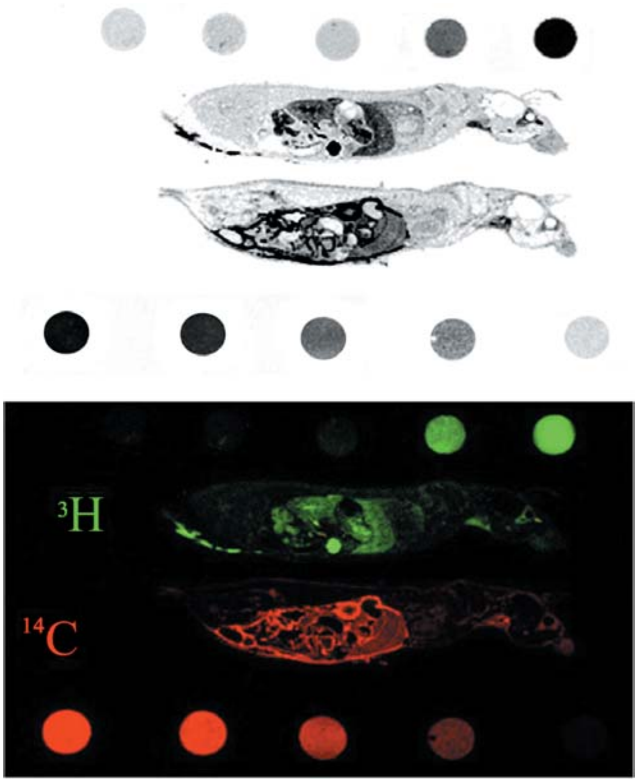


**Fig. 6.** Simultaneous measurement and separation of $^{3}$H and $^{14}$C labels with the $\beta$-imager

a scanner is that you deliver 100 to 1000 times less radiation. On average the doctors were giving 6 radios per child per year. With this they give only the equivalent of one. That makes them happy. Can you become rich with it? This is not clear! The high-energy physicist is a little bit like a kid. When the competitors are General Electric, Philips and Siemens, he discovers that he counts for nothing. Unless the law obliges us to decrease irradiation levels for children you may get nowhere. You depend on little things, whether insurance reimburses this type of radiography or not, for example. But there is still a great subjective pleasure working in this field.

Now let me go to an activity which I find fascinating. Six or seven years ago, Leon Lederman invited me to visit a ghetto where he was trying a pedagogical method called “Hands-on”. In fact it was one of seven or eight similar experiments in the United States, partly financed by the National Science Foundation, which are using slightly different approaches but all based on a simple idea: children are like scientific researchers. It is certainly true that scientific researchers can be like children, which you know, when you have spent some time at CERN. Children want to learn. Physicists go to the lab because they want to have an answer to questions. Young children are constantly questioning the mysteries of the surrounding world. If you provide them with good equipment, which doesn’t cost very much, you then discover that you can drastically improve the way they learn. They learn to make a hypothesis, they learn how to do an experiment, to check the hypothesis

**Fig. 7.** 2-D radiographs acquired with EOS, a 2D–3D low irradiation dose scanner (3D reconstructions are superimposed)

and they learn how to write and read, to discuss things with each other and communicate. And it is of great efficiency. We started with 10 people, sent by the Ministry of Education, who came with me to visit a school in Chicago. They were trusted, because they were important people in the French education system and they came back full of enthusiasm. And to my surprise we have now reached the stage where we have 12% of teachers in France who are contaminated.

In China, I have been to Shangai, and other places where they plan to equip 30 towns to join this venture. In Latin America we have seen the same move because it corresponds to something, which is now a universal need. Education is considered by the European Community as having a top priority. By the year 2010 they want to have revolutionized the education system throughout Europe. They are going to have the money but I am not sure that they know how to do it. The ideas come from pioneers, in the States or in many other places who have developed and practice this method of teaching. I have had the privilege of working on the dissemination of the method under four Ministers of Education, who all helped us, some more, others less. It appears to me that to progress rapidly we should be inspired by the experience of CERN. The cost of CERN has been roughly one billion dollars, every year for 40 years. We, half jokingly told the politicians: “give us one billion dollars every year for 30 years and we will give you a renovated educational system”. That looked like pure demagogy, but when I told them there are 50 million children and it costs 15 euros per child, every year, they could easily find the same number as we did. Now, finally, we don’t really need that much.

I have just come back from Stockholm where I spent three days with friends of the Royal Academy and also with a group, which is involved in the same reform. They have done some wonderful work over 5 years and we are proposing that the European Community give us enough money to start with some towns which are going to be “pilot towns”. I am convinced that if we succeed, we will rapidly contaminate the continent. We don’t need the billion dollars per year. We can stay decentralized. We don’t need to have many civil servants in one town. We can make use of Internet. In France, we have a site, with 80 scientists permanently answering questions put to them by teachers because the main problem is to teach the teachers. When the Chinese Vice-Minister of Education visited a school with me, she said: “Mr. Charpak, it is the best apprenticeship I have seen for scientific debate”. Because in their country like in many others, the tradition is that a teacher is a master, knowing the truth, to whom you cannot say: “We don’t agree with you, you don’t understand the problem” while in these “hands-on” classes, the teachers learn to say, when they are stuck, that they are like scientists, do not know everything and will give the answer next time.

Working in this field I must say I have the feeling that I use many things I have learnt from my life at CERN. We have to design a new international organization to help us make this big jump. We have serious support from some political leaders because they like our moves. They appreciate the fact that children are going to learn how not to follow gurus who preach the truth to them because they have learnt it from books. They learn how to check affirmations and make up their own mind by experimenting. And this can be a major contribution of science to the appeasement of many conflicts in our society.

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