NEUTRINO PHYSICS IN A FINE-GRAINED CALORIMETER

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Introduction

How do neutrinos interact with quarks and electrons? Do neutrinos couple through the neutral current to the same objects inside the nucleon as they do through the charged-current interaction? These are some of the questions being probed with a fine grained neutrino detector in Lab C. Although the weak neutral current has been studied for the last ten years, there is a level of experimentation on the weak neutral current which is comparatively unexplored. That level of experimentation is to study the weak neutral current interaction with full kinematic reconstruction. These experiments require a special type of neutrino detector which is capable of determining the direction of energy flow, the nature of the neutrino reaction products as well as the energy of these products. Since many reactions of interest have extremely small cross sections, the detector must be massive. We have recently constructed such a detector and have used it to obtain data, presently being analyzed, on the weak neutral current.

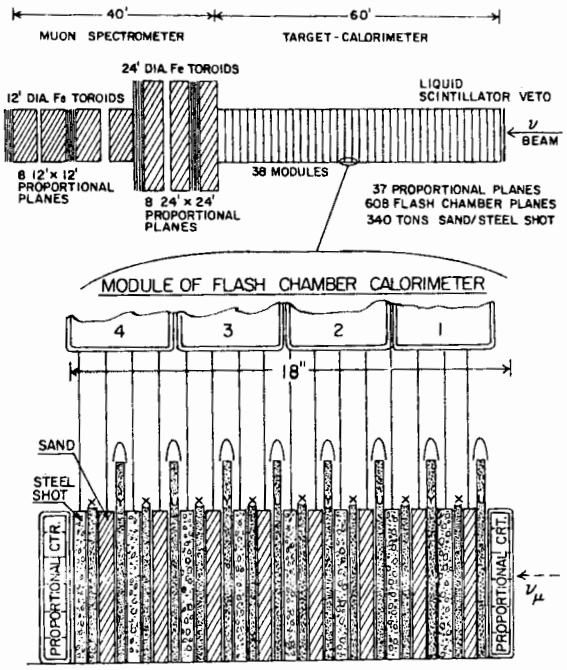
The Detector

To build a massive fine-grained neutrino detector requires the construction of an enormous number of detection elements. Unless these detection elements are made cheaply and simply, the costs of such a dectector would be prohibitively large. Our detector is based on plastic flash chambers (originally developed by M. Conversi)[1] and on proportional tube chambers, both of which are straightforward to construct and operate, and allow fine-grained sampling of the neutrino reaction products. Our detector has roughly 445,000 active detection elements in the form of 5mm×5mm flash chamber cells.[2]

The flash chamber-proportional tube calorimeter, is 60 feet long and has a 12ft×12ft cross section and a mass of approximately 340 metric tons. The flash chambers are used to determine the pattern of the neutrino reaction products thereby furnishing an identification of the event type as well as determining the energy and angle of energy flow. The proportional tube chambers

are used to trigger the flash chambers and to provide an additional measurement of the energy of the shower. The layout of the detector is shown in the figure below.

E-594 NEUTRINO DETECTOR



Layout of the detector.

The flash chambers are arranged in three views (x,y,u) with cells which run 0°, 80°, 100° relative to the horizontal plane. The flash chambers are read out electronically by means of a magnetostrictive wand. Each flash chamber plane is sandwiched between a sand-filled plastic extrusion plane and a steel shot filled extrusion plane which forms the mass of the detector.

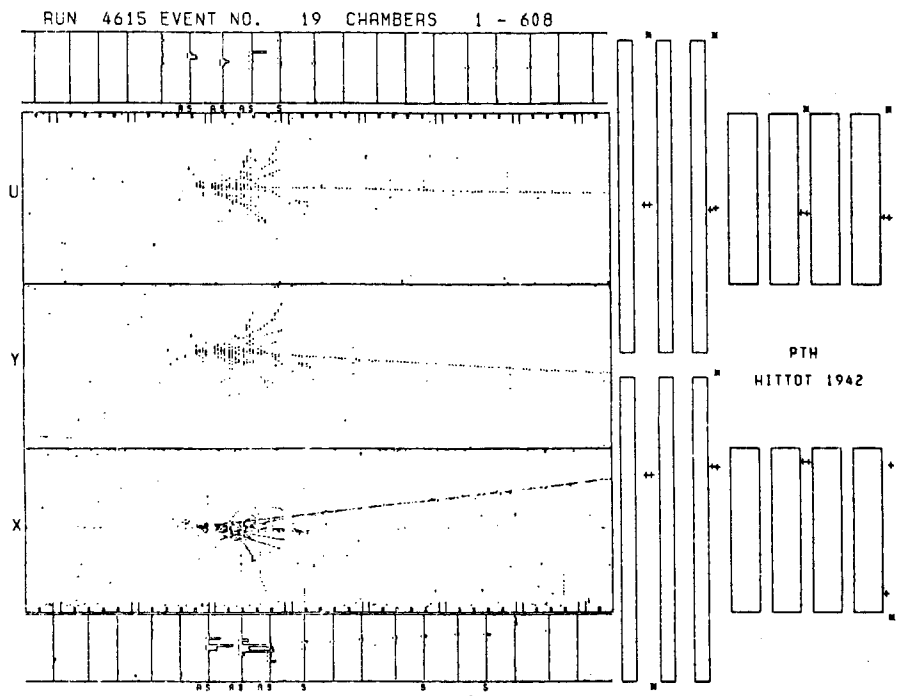
The proportional tube planes are located every 16 flash chamber planes (one module) in an alternating horizontal-vertical pattern. Each module weighs approximately 9 tons.

The proportional tube chambers are instrumented with an amplifier for every 4 wires with a wire separation of 1 inch. This high level of segmentation gives pattern recognition at the trigger level as well as analog information on the energy deposition.

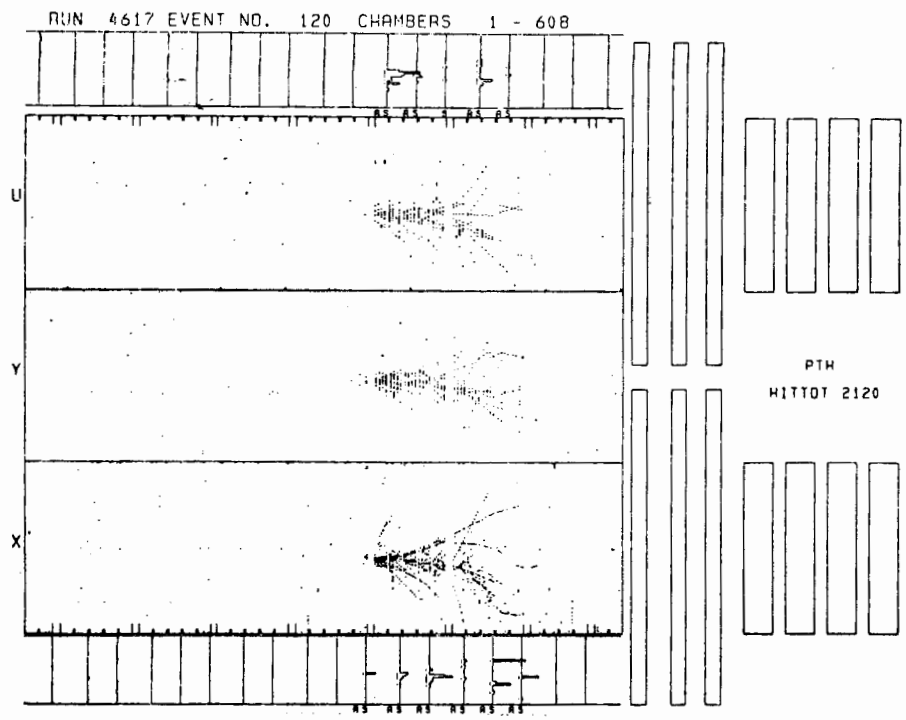
This arrangement of flash chambers-proportional tube chambers-sand and steel shot has an average radiation length X_0 of 12 cm sampled every 0.22 X_0 by the flash chambers and every 3.5 X_0 by the proportional tube chambers. The average absorption length λ is 96 cm (135 g/cm^2) and is sampled every 0.03 λ by the flash chambers and every 0.50 λ by the proportional tube chambers. The average density is 1.4 g/cm^3 and the average Z is approximately 21. This property of low density and low Z is important in achieving good energy flow measurements for hadron showers.

Downstream of the flash chamber-proportional tube chamber calorimeter is an iron toroid muon spectrometer. This spectrometer is instrumented with double plane proportional tube chambers with a one-inch resolution. These toroid proportional tube planes are being upgraded with a drift system to give a 1 mm resolution.

The pattern recognition capabilities of the detector are evident in the figure below, which shows a display of a typical charged-current interaction and a typical neutral current interaction.



Typical charged-current event showing the hit pattern in the flash chambers and the proportional tubes.



Typical neutral-current event.

Shown are the 3 views of flash-chamber planes (x,y,u on the display). Each dot drawn on the display represents a struck cell in a flash chamber. The total number of hit flash chamber cells is roughly proportional to the energy of the shower. Thus the energy of the shower is determined from the number of hit cells.

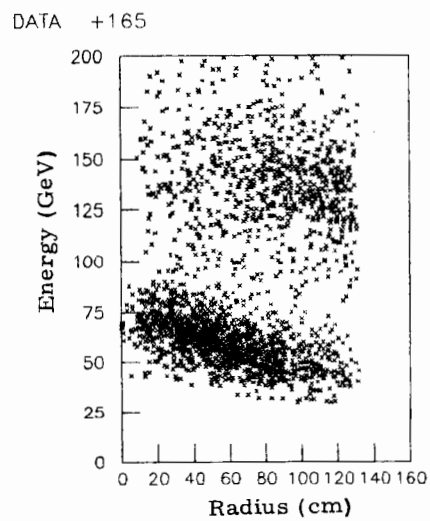
Also shown in the figure are the pulse heights of the proportional tube planes which provided the trigger of this event. These pulse heights appear as bar graphs along the lower and upper edges of the picture for the horizontal and vertical plane orientations, respectively.

The toroids are shown at the right of the figure. The "+" signs indicate the track of the muon through the spectrometer in the horizontally (bottom) and vertically (top) oriented proportional planes.

The Experimental Program

There are two major objectives of the program to study neutrino interactions in our fine-grained neutrino detector. These objectives are 1) to study the $x = Q^2/2m\nu$ dependence of deep inelastic neutral current interactions, and to compare this with the corresponding dependence of charged current interactions, and 2) to study pure leptonic neutrino interactions such as $\nu_\mu e^- \to \mu^- \nu_e$ and $\nu_\mu e \to \nu_\mu e$ and neutrino oscillations by searching for missing energy in events with a ν_μ or ν_e quasi-elastic scattering signature. These studies will test the standard gauge theory of electro-weak interactions and search for the exotic in high-energy neutrino interactions.

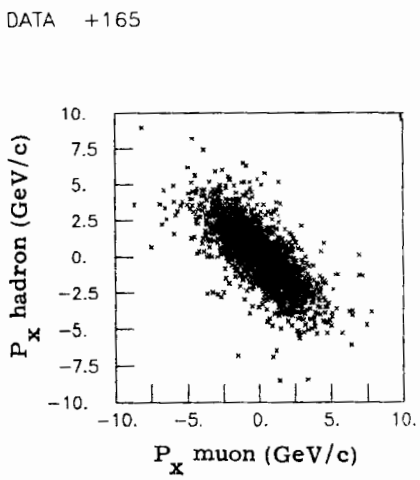
These analysis projects are in progress and thus at the present time various tests are being performed on the data. To demonstrate the energy reconstruction of the incident narrow band beam used in the deep inelastic scattering experiment, we show in the figure on the right, the energy versus radius correlation. The π and K bands are clearly visible. To demonstrate the energy flow technique for the recoil hadron shower (the essence of the x-scaling variable measurement for neutral current events) we show in the figure on the left of the next page, the transverse momentum of the hadron shower versus the transverse momentum of the muon for charged current events. We see that the transverse momentum is balanced and thus the energy flow of the hadron shower can be determined.



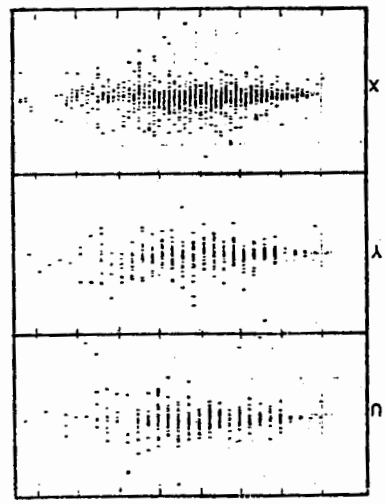
The energy versus radius correlation of the reconstructed incident neutrino energy from charged current interactions.

In our 1982 narrow band data sample of deep inelastic events we have approximately 19K ν_μ reconstructed events and 4.3K $\bar{\nu}_\mu$ reconstructed events. These should allow a good comparison of the neutral current/charged current x-distributions.

The study of pure leptonic neutrino interactions has been focused on the study of $\nu_\mu e^- \to \mu^- \nu_e$ scattering in the narrow-band beam, and on a demonstration of the resolution of the detector by studying $\nu_\mu e \to \nu_\mu e$ in data taken during an engineering run in 1981. Additional effort has been invested in setting a limit on $\nu_\mu \to \nu_x$ oscillations which exploits the pattern recognition and the selective triggering capabilities of the detector.[3]



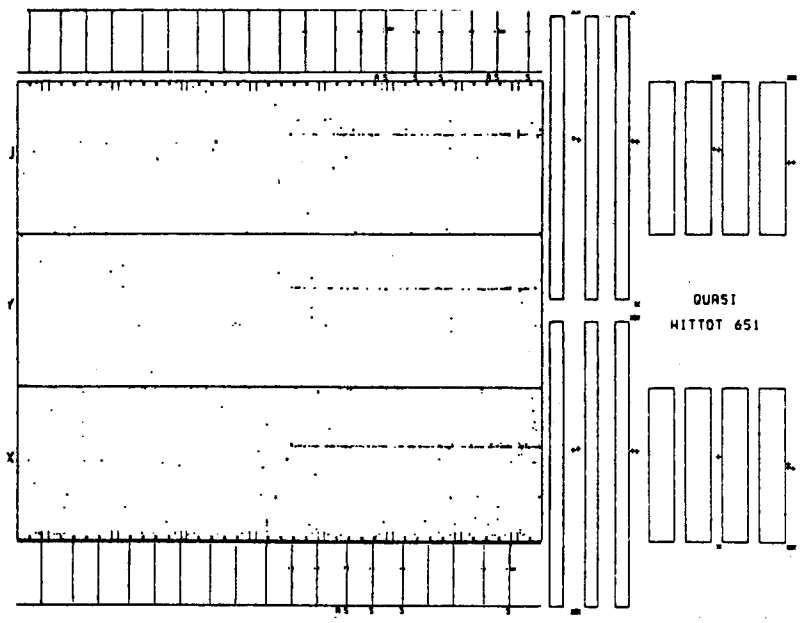
The transverse momentum (X-view) of the hadron shower versus the transverse momentum of the muon for charged current events.



A typical $\nu_\mu e \to \nu_\mu e$ candidate event. An expanded scale is used.

The most difficult aspect of studying these rare neutrino interactions is to identify the events in the prescence of a very large background. The fine-grained sampling and selective triggering schemes of our detector enable us to do this.[4] The figure on the right shows a $\nu_\mu e \to \nu_\mu e$ candidate event which has the signature of a clean recoil electron shower and no hadronic debris. The figure on the next page shows a $\nu_\mu e^- \to \mu^- \nu_e$ candidate event which has a clean muon track and no other visible recoil particles.

In summary, the fine-grained flash chamber-proportional tube neutrino detector we have built is yielding data on deep inelastic scattering and on rare neutrino interactions. A concentrated effort is now underway to exploit fully its unique sampling properties.



A $\nu_\mu e^- \to \mu^- \nu_e$ candidate event.

References

[1]M. Conversi and L. Federici, Nuclear Instrum. Methods **151**, 93 (1978).

[2]D. Bogert et al., IEEE Trans. Nucl. Sci. **NS-29**, 363 (1982).

[3]D. Bogert et al., Proceedings of the XVIII Rencontre de Moriond, La Plagne, France, March 1983.

[4]D. Bogert et al., Proceedings of the XVII Rencontre de Moriond, Les Arcs, France, March 1982.

Assembly of the first production central calorimeter module for CDF in Industrial Building 4. The steel was cut and welded at Purdue. The hadron scintillator and light pipes were cut and fabricated in Italy. The shower counter scintillator was made and cut in Japan. The shower counter light pipes were made at ANL. The muon counters were made at the University of Illinois. All of these pieces came together and were assembled at Fermilab.
(Photograph by Fermilab Photo Unit)

[Editors' Note: Many of our readers may be interested in the recent Symposium, held in the Vatican, honoring the 350th anniversary of the publication of Galileo's famous "Dialogues." We reproduce here the remarks made to an audience of scientists by his Holiness, Pope John Paul II.]

DISCOURSE OF HIS HOLINESS POPE JOHN PAUL II FOR THE INAUGURATION OF THE SYMPOSIUM ORGANIZED ON THE OCCASION OF THE 350TH ANNIVERSARY OF THE PUBLICATION OF THE BOOK BY GALILEO GALILEI ENTITLED **DIALOGHI SUI DUE MASSIMI SISTEMI DEL MONDO**

Ladies and Gentlemen,

In addressing myself to you, who represent with honour the rich horizons of modern science, I wish in the first place to thank you cordially for your visit, and to tell you that your presence here this morning seems to me to have a deeply symbolic value, for you attest to the fact that between the Church and Science a fruitful dialogue is being developed.

And I am not alone in welcoming you. My brothers, the Cardinals of the Holy Roman Church present in Rome, and other leading figures of the Holy See - whom I am pleased to greet with you and whom I likewise thank for being here - testify to the importance that the Church attributes to this dialogue.

We cast our minds back to an age when there had developed between science and faith grave incomprehension, the result of misunderstandings or errors, which only humble and patient re-examination succeeded in gradually dispelling. And so we should rejoice together that the world of science and the Catholic Church have learned to go beyond those moments of conflict, understandable no doubt, but nonetheless regrettable. This was the result of a more accurate appreciation of the methods proper to the different orders of knowledge and the fruit of bringing to research a more rigorous attitude of mind.

The Church and science itself have reaped great profit from this and have discovered through reflection and sometimes painful experience the paths that lead to truth and objective knowledge.

To you who are preparing to mark the 350th anniversary of the publication of Galileo Galilei's great work, **Dialoghi sui due massimi sistemi del mondo**, I would like to say that the Church's experience, during the Galileo affair and after it, has led to a more mature attitude and to a more accurate grasp of the authority proper to her. I repeat before you what I stated before the Pontifical Academy of Sciences on 10 November 1979:

> "I hope that theologians, scholars and historians, animated by a spirit of sincere collaboration, will study the Galileo case more deeply and, in frank recognition of wrongs, from whichever side they come, will dispel the mistrust that still forms an obstacle, in the minds of many, to a fruitful concord between science and faith, between the Church and the world. I give all my support to this task, which will be able to honour the truth of faith and of science and open the door to future collaboration" (**AAS** (1979), pp. 1464-1465).

As you know, I have asked for the formation of an interdisciplinary research team for the careful study of the whole question. Its work is progressing very encouragingly, and there are good grounds for hoping that it will make an important contribution to the examination of the whole matter.

The Church herself learns by experience and reflexion, and she now understands better the meaning that must be given to freedom of research, as I said to the representatives of the Spanish Universities on 3 November 1982:

> "The Church upholds freedom of research, which is one of the most noble attributes of man. It is through research that man attains to Truth - one of the most beautiful names that God has given himself. This is why the Church is convinced that there can be no real contradiction between science and faith, for the reason that the whole of reality ultimately comes from God the Creator. This is what is stated by the Second Vatican Council (cf. **Gaudium et Spes**, 36). I have stated this myself on a number of occasions in addressing men and women of science. It is certain that science and faith represent two different orders of knowledge, autonomous in their processes, but finally converging upon the discovery of reality in all its aspects, which has its origin in God" (cf. Discourse in Cologne Cathedral, 15 November 1980, No. 8, **L'Osservatore Romano**, 4 November 1982, p. 2).

One thus preceives more clearly that divine Revelation, of which the Church is the guarantor and witness, does not of itself involve any particular scientific theory, and the assistance of the Holy Spirit in no way lends itself to guaranteeing explanations that we would wish to profess concerning the physical constitution of reality.

The fact that the Church has been able only with difficulty to make advances in such a complex sphere should neither surprise nor scandalize us. The Church, founded by Christ who called himself the Way, the Truth and the Life, still remains made up of individuals who are limited and who are closely bound up with the culture of the time they live in. So it is that she declares that she is always interested in research concerning the knowledge of the universe, whether physical, biological, or psychological. It is only through humble and assiduous study that she learns to dissociate the essentials of faith from the scientific systems of a given age, especially when a culturally influenced reading of the Bible seemed to be linked to an obligatory cosmogony.

To return to the case of Galileo, we certainly recognize that he suffered from departments of the Church. But in his time, there were not lacking Catholic centres which were already cultivating with great competence, over and above theology and philosophy, disciplines such as history, geography, archaeology, physics, mathematics, astronomy, and astrophysics; and these studies were considered necessary for a better knowledge of the historical evolution of man and of the secrets of the universe. Brilliant forerunners had even put Catholics on the guard, urging them not to set up an opposition between science and faith. This is what I wished to affirm, on 15 December 1979, at the Gregorian University, whose researches and professors were known, in his own time, to Galileo:

> "And while we must recognize that students of that time were not unaffected by their cultural milieu, we can nevertheless note that there were brilliant forerunners and freer minds, like Saint Robert Bellarmine in the case of Galileo Galilei, who wished that useless tensions and harmful rigidities between faith and science could be avoided" (**AAS** (1979), p. 1541).

These facts confirm us in the indispensable need for a frank and open dialogue between theologians, scientific specialists and those who exercise leadership in the Church.

Hence we can see that the age-old relationships between the Church and science have brought Catholics to a more correct understanding of the sphere of their faith, to a sort of intellectual purification and to a conviction that scientific study deserves a commitment to unbiassed research which, in the final analysis, is a service to truth and to man himself. We should add that the Church recognizes with gratitude all that she owes to research and science. I had occasion to say this to the Pontifical Council for Culture on 18 January 1983:

> "Let us think of how the results of scientific research help us to know the universe better, to understand better, to understand better the mystery of man; think of the advantages which the new means of communication and contact among people offer to society and to the Church; let us think of the ability to produce incalculable economic and cultural wealth, and especially to promote the education of the masses, and to cure diseases previously thought incurable. What admirable achievements! All this is to man's credit. And all this has greatly benefitted the Church herself, in her life, her organization, her work and her own activity" (No. 6 **L'Osservatore Romano**, 19 January 1983, p. 2).

And if we address ourselves now more directly to the scientific world, does one not see today how the greater sensitivity of scholars and researchers to spiritual and moral values brings to your disciplines a new dimension and a more generous openness to what is universal? This attitude has greatly facilitated and enriched the dialogue between science and the Church.

It is of course required that you adopt a method of advanced specialization so as to carry ever further forward your discoveries and your experiences, and one cannot help but admire the rigour and intellectual honesty, the disinterestedness and self-denial which so many researchers bear witness to as they dedicate themselves to their studies with a real spirit of mission.

Moreover, the scientific world, having now become one of the principal sectors of activity in modern society, is itself discovering, in the light of reflection and experience, the extent and at the same time the seriousness of its responsibilities. Modern science and the technology that derives from it have become a veritable power and form the object of socio-economic policies or strategies, which are not neutral as regards the future of man.

Ladies and gentlemen, you who are engaged in the sciences: you possess considerable power and responsibility, and these can become decisive for the orientation of tomorrow's world. On many occasions I have expressed the Church's great esteem for the collective effort made by people of science to ensure that the urgent objectives which are required by the pursuit of the development of man and peace may prevail. You know that a moral transformation is needed if we want the scientific and technical resources of today's world to be effectively placed at the service of man. At Hiroshima, before the United Nations University on 25 February 1981, I stated:

> "The people of our times possess, in the first place, tremendous scientific and technological resources. And we are convinced that these resources could be far more effectively used for the development and growth of peoples...All of this obviously presupposes political choices, and, more fundamentally, moral options. The moment is approaching when priorities will have to be redefined. For example, it has been estimated that about a half of the world's research workers are at present employed for military purposes. Can the human family morally go on much longer in this direction?" (**AAS** 73 (1981), pp. 424-425).

Ladies and gentlemen, you enjoy immense moral influence in order to assert the properly humanistic and cultural objectives of science. Strive to defend man and his dignity at the centres of decision-making which govern scientific policies and social planning. You will always find an ally in the Church, each time that you strive to promote man and his authentic development.

It is also assuredly from within that the Church concerns herself with your work. For none of the things that can deepen knowledge of man, nature and the universe can leave us indifferent. All scientific progress, pursued with rectitude, honours humanity, and is a tribute to the Creator of all things. Your investigations constitute an extension of the marvellous revelation that God gives us in his work of creation. The Church does not first turn to your discoveries in order to draw from them facile apologetic arguments for strengthening her beliefs. Rather she seeks, thanks to you, to expand the horizon of her contemplation and of her admiration for the clarity with which the infinitely powerful God shines through his creation.

For the believer, the most specialized research can thus become a highly ethical and spiritual act. For the saints, study was prayer and contemplation.

Yes, the Church appeals to your capacities for research in order that no limit may be placed upon our common quest for knowledge. Your specialization of course imposes upon you certain rules and indispensable limitations in investigation; but beyond these epistemological limits, let the inclination of your spirit carry you towards the universal and the absolute. More than ever before, our world needs intellects capable of grasping the whole picture and of enabling knowledge to advance towards humanistic understanding and towards wisdom. In a word, your knowledge must blossom into wisdom; that is, it must become the growth of man and of the whole man. Open your minds and hearts fully to the imperatives of today's world, which aspires to justice and to dignity founded on truth. And you yourselves, be ready to seek all that is true, convinced that the realities of the spirit form part of what is real and part of the whole Truth.

Ladies and gentlemen, your task is noble and very great. The world looks to you and expects from you a service which matches your intellectual capacities and ethical responsibilities.

May God, the Creator of all things, who is present in the immensity of the universe and in each of our hearts, accompany you in your work and inspire your admirable work.