Q. Majorana's Experiments on Gravitational Absorption: Further Documents and Manuscripts

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ABSTRACT. Our intention is to present Q. Majorana (1871–1957) further documents, experimental manuscripts and results on the hypothetical physical effect of gravitational absorption. Majorana carried out his experiments thanks to two main apparata, the first at the Polytechnic of Turin (1918-1919; 1919-1921), the second at the Institute of Physics of Bologna University (1922-1924). A comparison of the results obtained by Majorana will be discussed, together with some possible meanings and modern conceptual perspectives of his research.

Forward

In the first half of the twentieth century Quirino Majorana (1871-1957), uncle of the famous theoretical physicist Ettore, was one of the most important Italian physicists thanks to his many-sided interests and his great skill as an experimenter. He was involved in scientific activity for more than sixty years, publishing more than 120 papers concerning many topics, such as electric discharges in gases, X rays, ballistics, the Volta effect, magnetic birefringence, wireless telephony, gravitational absorption and the experimental proof of the principles of Einstein's special theory of relativity [1]. Nevertheless, his fame seems to be not adequate to his merits and to his reputation as a scientist who had important honours and was chosen for important appointments throughout his long scientific life.

Probably, this historical opinion came from Majorana's attitude towards physical laws belonging to widely accepted theories, such as the second principle of the theory of special relativity and the universal law of gravitation [2]. Always endeavouring to confirm or break these laws, Majorana constructed complex experimental apparatuses which he used to investigate on the constancy of the speed of light and on the absorption of the force of gravity by matter. His deep care for experimental details allowed him to reach incredible levels of accuracy.

In this paper our purpose is to review Majorana's experiments on these topics in order to gain a better insight about him as a scientist, and, consequently, as a man.

Bibliographical Notes

"The hope to obtain some new result and sometimes to achieve it has always been the real purpose of my life"[3] in this sentence, quoted by Prof. Eligio Perucca in his commemoration of Q. Majorana, we can see the most important feature of Quirino Majorana's personality.

He was born in Catania (Sicily) on 28th of October 1871, and studied engineering in Rome, where he received a degree with Prof. Giuseppe Pisati when he was twenty years old; he stayed in Rome until 1914. In the same university he got a degree in Physics in 1893 with Prof. Pietro Blaserna, to whom Majorana was an assistant from 1894 to 1904. In 1904, for his scientific ability, he was appointed as Director of the Central Telegraph Institute by a committee formed from the best Italian physicists of that time: Battelli, Blaserna and Righi. In 1914 he was appointed to the post of full professor of Experimental Physics in the Polytechnic of Turin, where he stayed until 1921, when he was appointed to the post of Professor of Physics in Bologna, after the death of Prof. Righi in 1920. Majorana remained in Bologna until 1941, when he retired. He was then designated emeritus professor of

Bologna University and kept working at the Institute of Physics thanks to the kindness of his successor, Prof. Giorgio Valle (1887-1953). In 1954, on the invitation of V. Gori, director of the Advanced Institute of Telecommunications, he began working in this Institute, where he could pursue his interests concerning physics. On 31 July 1957 at the age of 86 he died in Rieti.

Quirino Majorana received many honours [4]: he was a member of the Academy of Lincei, of the Academies of Turin, Catania, Modena, Barcellona and of London's Royal Institution; for a long time, he was director of the School of Specialization for Radio communications in Bologna; he was the head of the Italian Physical Society from 1925 to 1947. Finally, he was a rear admiral of the Italian Navy. Among the prizes he won some must be mentioned, such as the Santoro Prize of the Academy of Lincei (1909) for his achievements in wireless telephony; the Mussolini prize of the Academy of Italy (1940), very important at that time; the Righi Medal, awarded to him by the Italian Society of Electrical Engineering in 1940.

To describe briefly a complex personality such as Q. Majorana's is a hard task: we shall restrict ourselves to a few remarks, nevertheless sufficient to give an idea of who he really was. Majorana was used to work alone, except for the remarkable cooperation with Ettore Majorana, which is documented by a rich and unpublished correspondence belonging to the period from 1931 to 1937, which we have studied[1]. The cooperation was so intense, direct and continual so as to throw additional light upon the personality of Ettore.

About this, we think that the following sentences are particularly meaningful: "I wanted to ask you one more thing. In the development of this research I often made use of your help. Even last year you did not allow me to quote your name. On the other hand, I think that in a full description of the observed phenomena, it is useful to give a picture of some of your suggestions. Thus I ask you: Do you think this can be considered appropriate by the readers? Do you persist in denying me the pleasure of quoting your name? And, do you behave like this because of your modesty or because of the simplicity of the topic under examination? But in this case, do you think that your uncle can overstress your erudition without doing something deserving censure? Thanks. Your uncle Quirino"[2].

Most of Q. Majorana's papers were therefore signed by him alone. He was not attracted by experimental researches which came - let us say - into "fashion" during the sixty years of his scientific activity: he always preferred to devote himself to "subtle researches, difficult to pursue"[3]. He was a first class experimental physicist, and he could always infinitely decompose the phenomenon under examination, investigating all the aspects which could hide the real goal of the research: among the solutions he gave to the many experimental problems he had to tackle, some are really ingenious.

As a teacher, he greatly improved a method of conspicuous effectiveness and cultural penetration, which is the one of the experimental lecture, where the physical laws which were described were wisely explained with experiments. After him, this method almost disappeared, but there are still those who remember the spectacular quality of those lectures. His lectures on experimental physics were full of experiments, sometimes difficult, always executed without fuss [1]. Some people did attend his lectures for the only pleasure they found in the clear and intuitive exposition of the physical phenomena, and of their sometimes original explanation [1]. He always considered experimental skill mandatory for a physicist and even more mandatory was for him the experimental "mentality," as his own words clearly indicate: "unfortunately in Italy experimentation is not common and this is often attributed to the inadequacy of equipment. I think that this is due to the lack of will; if one has faith and enthusiasm for one's own research, the means for it can always be found (except for cumbersome materials)"[1].

The Experiments on the Second Postulate of the Special Theory of Relativity

The interest in Einstein’s theory of relativity lasted throughout all Majorana’ scientific life, and led him to plan and execute several experiments in order to assess the correctness of its principles. Majorana made experiments on the second postulate of the special theory of relativity in the years 1916-18 and in 1934: in this paper we are concerned with these experiments. Later on, after the Second World War, Majorana came again to deal with Einstein’s theories, but from a different point of view, that is conceptual, logical and critical[3].It must be said that Majorana succeeded only in confirming the postulate of constancy of the speed of the light c, and if this did not fully satisfy his deep skepticism concerning Relativity, he always admitted the validity of the postulate which he investigated experimentally [5].

In his autobiographical notes, Majorana recalls the origin of his researches about relativity: “Since then (the appearance of the theory) I was struck by the innovating boldness of the German physicist, which was not grounded upon any new experimental or natural phenomenon. Thus, I doubted, like many other physicists, of the reliability of his theories. I think that my attitude was the result of my particular method of research, always grounded on the observation of real facts, even if their ultimate essence may be hidden to the human faculty of reason”[6].

Thus, Majorana’s experimental attitude must be examined within a cultural context which was, even near the Twenties, strongly anti- relavitistic[4]. Majorana himself contributed in describing the attitude of those years: “even if (the relativistic theories) ... are widely appreciated and trusted among mathematical physicists, mathematicians and, partially, astronomers, they are not accepted, at least frankly, by the majority of experimental physicists”[7].

Majorana devoted the first experiment on the second postulate of the special theory of relativity to studying the speed of the light reflected by a mirror moving respect to the observer. The experiment was carried on in Turin in 1916 and its results were published in 1917 and 1918[8],[9],[10],[11]. The main feature of the phenomenon to be studied is rather simple. Referring to Fig. 1, let’s consider a light source S moving at the speed v towards an observer in O. Which will be the wave-length of the light arriving in O? There are two possibilities.

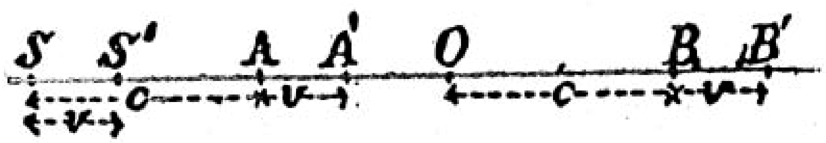

Fig. 1

1. RELATIVISTIC CASE (FIXED ETHER)

If the theory of relativity holds, the speed of the light does not depend on the motion of the source. In a second the source moves across the distance[5] SS’= v. Let us consider the n waves emitted in a second by the source in a point P of the segment SS’, at a distance x from S and that in this point it emits a wave: we furthermore assume that the process of emission of electromagnetic waves is constant. If t is a time interval of one second, we wonder where the source and the wave will be after time t. From the relationship distance = speed x time we can write:

$$y - x = ct \; ; \; v - x = vt \tag{1}$$

where *y-x* is the distance travelled over by the wave and *v-x* is the distance travelled over by the source during time t. Eliminating t from the previous relationship, we obtain:

$$\frac{y-x}{c} = \frac{v-x}{v} \tag{2}$$

that is:

$$y = x + c\frac{(v-x)}{v} \tag{3}$$

y is the place where the electromagnetic wave will be after the time t. If point P coincides with S, then x=0, and, from (3) we obtain y=c; if, on the contrary, the point P coincides with S', then x = SS' = v and from (3) we obtain y=v. Thus, the waves emitted in the segment SS' will be in the segment S'A=c-v. In the same time interval, at point *0* will arrive *n'* waves which are confined in the segment OB = c; this - under the above quoted hypothesis that the process of emission of
electromagnetic waves is constant - will be:

$$\frac{c-v}{n} = \frac{c}{n'} \tag{4}$$

that is:

$$n' = \frac{nc}{c-v} = \frac{n}{1-{}^{v}\!/_{c}} = \frac{n}{1-b} = \frac{n}{1-b}\frac{1+b}{1+b} = \frac{n(1+b)}{1-b^2} \cong n(1+b) \tag{5}$$

where b = v/c, and, in the last equation we neglected the quantities of the order of b^2; moreover, as $c = nl = n'l'$, from (5) we obtain:

$$\frac{n'}{n} = \frac{l}{l'} = (1+b) \tag{6}$$

that is, analogously to what we wrote for equation (5):

$$l' = l(1-b) \tag{7}$$

2. BALLISTIC CASE (EMISSIVE HYPOTHESIS)

If ballistic theory holds, the speed of light c must be added to the speed of the light source. We now wonder again where it will be after a second the electromagnetic wave emitted at a given instant at a point P of the segment SS'= v, at a distance x from S. In this case (1) becomes:

$$y - x = (c+v)t; \quad v - x = vt \qquad (8)$$

where the only difference with respect to (1)is that the speed of light *c* must be added to the one of the source v. Eliminating the time t from eq. (8), we obtain:

$$\frac{y-x}{c+v} = \frac{v-x}{v} \qquad (9)$$

that is:

$$y = x + (c+v)\frac{(v-x)}{v} \qquad (10)$$

As before, if point P coincides with S then x = 0 and from (10) we obtain y=c+v; if P coincides with S' then $x = SS' = v$ and (10) gives $y = v$. In a second the *n* waves emitted by the source S will be distributed in the segment $S'A' = c$. In the same amount of time *n'* waves will arrive at *O* and will be distributed in the segment $OB' = c + v$. Thus:

$$\frac{c}{n} = \frac{c+v}{n'} \qquad (11)$$

we can solve with respect to *n'*:

$$n' = n\frac{c+v}{c} = n(1+v/c) = n(1+b) \qquad (12)$$

The value we obtain for the frequency is thus the same as the one obtained in we the case of the relativistic theory. But the value of the wavelength is rather different: in fact, remembering that *c+v=n'?'*we can see that:

$$c + v = n(1+b)\,l' \qquad (13)$$

and this gives:

$$l' = \frac{c+v}{n(1+b)} = \frac{c}{n}\frac{1+b}{1+b} = \frac{c}{n} = l \qquad (14)$$

Thus, in this case, as to the frequency we obtain the same results (except for terms of the order of b^2) both with relativistic and with ballistic hypothesis. As to wavelength, we obtain values which differ for a term of the first order in b.

Majorana planned an experiment to decide whether relationship (7) or (14) was more appropriate to describe the phenomenon under examination. His method, based on the Doppler effect, consisted in measuring the variation of the wavelength of the light by measuring the shift of the fringes of interference (using a Michelson interferometer adapted by Majorana himself) given by the light reflected by a mirror which could move or not.

If *v* is the speed of the mirror orthogonal to its plane and J is the angle between the ray of light and the plane of the mirror, formula (7) becomes:

$$l' = l(1 - 2kb\cos J) \qquad (15)$$

if we use k reflections in our experimental apparatus (see Fig. 2a). On the contrary, if we use ballistic theory, we must use formula (14).

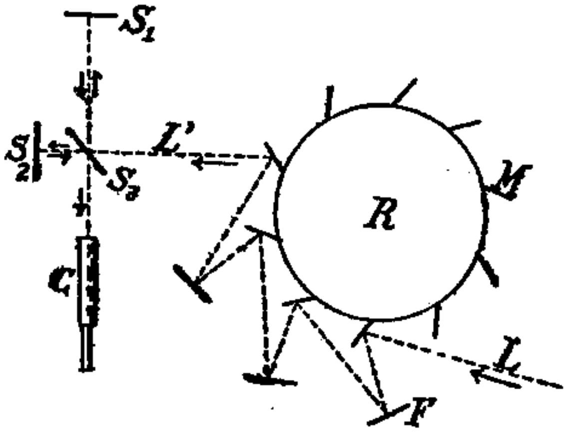

Figure 2a: Experimental apparatus for the demonstration of the constancy of velocity of the lisght reflected from moving mirror: rotating with mirrors, interferometer (original drawing). The original apparatus is still survived, (Museum of Physics, Bolonga University, Italy).

Majorana used an experimental apparatus (see Fig. 2b for a scale drawing) consisting in a wheel rigidly bearing some mirrors, the inclination of which was 29° with respect to the radius of the wheel. When rotating, the wheel could achieve the speed of 100 meters per second (360 km/hour). In addition to this, a system of fixed mirrors allowed multiple reflections, and this gave a value of k greater than 1: in Majorana's apparatus k=4.

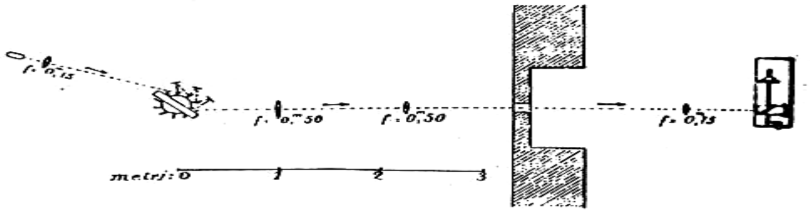

Figure 2b: Complete experimental apparatus: a scale drawing (original drawing).

As to the source of light, Majorana established he could not use white light; as Michelson had done, he therefore employed the green light of mercury (546 m)(Fig. 3).

The radiation produced by the electric arc employing mercury electrodes in a vacuum was filtered by solutions of neutral potassium chromate and of nickel chloride, to absorb violet and yellow light, respectively; thus Majorana obtained circular fringes of interference even for high values (32 cm) of the difference of the optical path of the two rays.

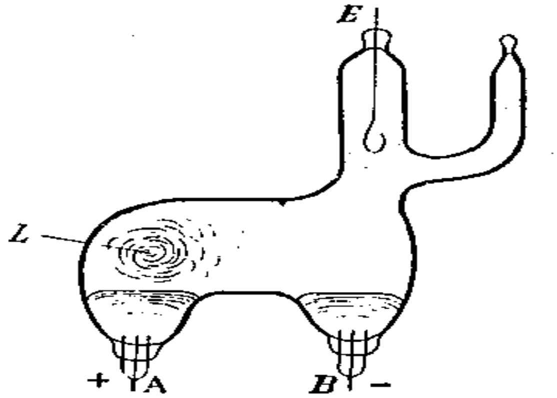

Figure 3: The source of light. Voltaic arc, the green light of mercury (original drawing). Several lamps like this are still survived (Museu of Physics, Bolonga University, Italy).

As to the expected experimental result, Majorana observed that, if *l* is the path difference of the interfering rays, the number of waves that can be found in it is K = *l*/?. If the second postulate of the special theory of relativity holds, we must use formula (7), and we will have *K'=(l/?')=(l/?)(1 + v/c)*. When the wheel passes from rest to movement, we should therefore observe a shift of the fringes equal to:

$$f = K' - K = \frac{l}{l'} - \frac{l}{l} = \frac{l}{l'}\frac{l - l'}{l} \qquad (16)$$

Due to the geometry of the experimental apparatus, the speed of the moving mirrors is equal to $pdg\cos a$, where *g* is the number of rounds per second of the wheel, *d* is its diameter and a is the angle between the plane of the mirrors and the normal to the edge of the wheel. If we substitute this expression for speed in (15) we obtain:

$$l' = l(1 - \frac{2kpdg\cos a\cos J}{c})$$

(17a)

$$\frac{l - l'}{l} = \frac{2kpdg\cos a\cos J}{c} \qquad (17b)$$

Thus, when the speed of rotation of the mirror varies from *0* to g rounds per second, the wavelength of the light varies from ? to ?'. The expected shift of the fringes of interference can be obtained substituting in (16) (?-?')/? with the righthand side of equation (17b):

$$f = \frac{l}{l'}\frac{l - l'}{l} = \frac{l}{l'}\frac{2kpdg\cos a\cos J}{c} \qquad (18)$$

Substituting in (18) the numerical values, Majorana obtained an expected value for *f* of 0.71. As a matter of fact, from his experiment he obtained a value between 0.7 and 0.8. He concluded in this way one of his papers on the subject:

> Thus, the experiment makes it possible to conclude that *the reflexion of the light by a moving metallic mirror does not alter the speed of the light in the air and therefore, with high probability, also in the vacuum*; at least, in the described experimental conditions (Majorana's italics) [ll].

In the same paper Majorana planned to complete his research, by repeating the experiment with a moving source of light: he made this in 1917- 18, right after his first experiment.

To carry on this new research, the results of which were published in 1918-19[12],[18], Majorana had to face additional experimental difficulties. In fact, if it had been relatively simple to find a reflecting device which could be put into motion, this was much more difficult for a source of light. This difficulty was stressed by Majorana together with the originality of his experiment: "As far as I know, it has never been attempted to prove the Doppler effect by means of the artificial motion of a source of light (only astronomical sources and the so-called 'canale' rays had been employed up to that time) the complexity of this research lies mainly in the necessity of providing the source with a reasonable speed"[12]. Majorana adds that the main goal of the experiments is not to take for granted the confirmation of the Doppler Effect, but to measure the speed of propagation of light.

For example, if one wants to achieve a peripheral speed of 100 meters per second (along a circular path), the main difficulties to be solved are represented by the centrifugal force and by the resistance of the air. In the first, it is desirable that the radius of the path is large and the number of the rounds per second is low, due to the fact that the centrifugal force increases with the square of the number of rounds, while the peripheral velocity increases only with the number of rounds. In fact, if m is the mass of the source, R is the radius of the circular path and g the number of rounds per second, the centrifugal force will be $4\pi^2 Rmg^2$, while the peripheral velocity is $2\pi gR$. Employing a diameter of 2 meters and a source mass (a small mercury tube) of 35g (Fig. 4).

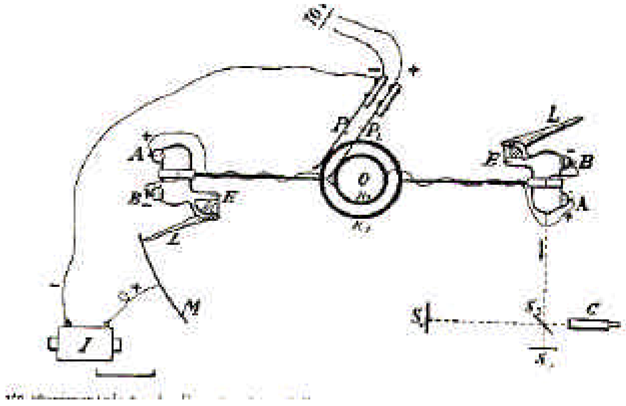

Figure 4: Experimental apparatus for the demonstration of the constancy of velocity of light emitted by a moving source (original drawing). The original device is still survived (Museum of Physics, Bolonga University, Italy).

Majorana obtained for the centrifugal force the value of 30 kg with a speed of 14 rounds per minute. This force was close to the maximum stress of the glass of the tubes, but they stood for a time sufficiently long to allow measures. The resistance of the air was minimized using subtle steel wires to connect the mercury tubes and the rotating shaft. To have an idea of the whole apparatus employed for this experiment, one can imagine putting the device shown in Figure 4 in place of the wheel shown in Figure 2b.

Using (18) and the characteristics of the apparatus Majorana obtained 0.226 as expected value for the displacement of the fringes, while he obtained from his experiment a value of 0.238, which was in good agreement with the theory. He conjectured: “We can infer that, given the experimental conditions and within the limits of accuracy of the observations, *the speed of light does not vary due to the motion of the source along the same direction of propagation* (Majorana’s italics)”[13].

Nevertheless, Majorana recommended considering the research still open, due to the fact that two important elements had not been taken into account in his experiments. On the one hand, in fact, it was necessary to consider the presence of the matter crossed by the interfering rays. Majorana conjectured that the speed of the light could even be not constant, but that the subsequent interactions of the light rays with the matter could offset this effect. On the other hand, Majorana stressed that his experiments had been carried on within the Earth’s gravitational field, which could have influenced in some way the measured effect. “While it is easy to imagine experiments not affected by the first (effect), it is not possible to predict if further experiments will demonstrate the influence of the second”[13].

Majorana resumed his experiments about the check of the constancy of the speed of light later on, in 1934, when he was already a famous physicist, who had succeeded Righi at the chair of physics in Bologna University thirteen years before. He restarted just from where he had stopped sixteen years before, that is, from the study of the propagation of the light in a vacuum. In fact, as we have already seen, the doubt his previous experiments had left with him was about the influence of the matter in the apparent constancy of the speed of the light.

The experimental apparatus he used (Fig. 5a) was formed by a wheel equipped with mirrors and put in a vessel where a vacuum had been created. The mirrors of the wheel were struck by the light of the source, which again employed the green light of mercury, and could in this way act as a moving source of light.

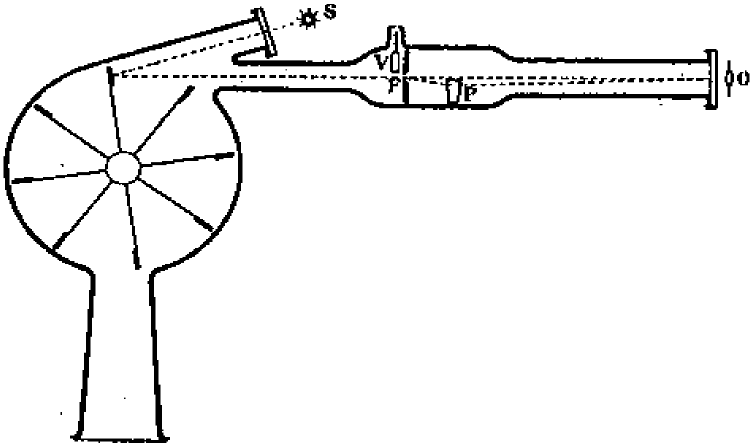

Figure 5a: Apparatus for the experimental demonstration in a vacuum of the constancy of velocity of the light reflected from moving mirror (original drawing). The original apparatus is still survived (Museum of Physics, Bolonga University, Italy).

The novelty was constituted by the interferential device, which was accurately described by Majorana in several papers [14], [15], [16], [17], and which was employed to show the displacement of the fringes of interference. The device which consisted of a slit F and of a prism P, was put in a vacuum. The light reflected by the mirrors went through the slit (10-20µ), undergoing the phenomenon of diffraction.

A part of the energy of the light rays reached directly the eye of the observer O (through an ocular external to the vessel and equipped with a movable grating), while another part passed through a prism P which was behind the slit and had a very small refractive angle a (about l°). Furthermore, just before the slit, it was possible to put or to remove a glass prism with parallel sides V equipped with an iron framework and moved by a magnetic device. In this way, it was possible to compel the light reflected by the mirrors to pass through the prism V or not. If the motion of the mirrors influenced the speed of the light and this influence could be offset by the fact that the light passed through the matter, this apparatus would demonstrate this: one should expect a displacement of the fringes formed by the direct ray and the ray passing through the prism P or not if the prism V was or not was placed before the slit. According to the same hypothesis, one should expect a displacement of the fringes if, in absence of the prism V, the speed of rotation of the mirrors was changed.

In case of presence/absence of the prism V Majorana assumed there would have been a displacement of the fringes if the ballistic theory held, because the *PO* ray would have propagated with the same speed as before, while the segments *FO* e *FP* would have crossed with different speeds if the prism V was present or not before the slit (Fig. 5b).

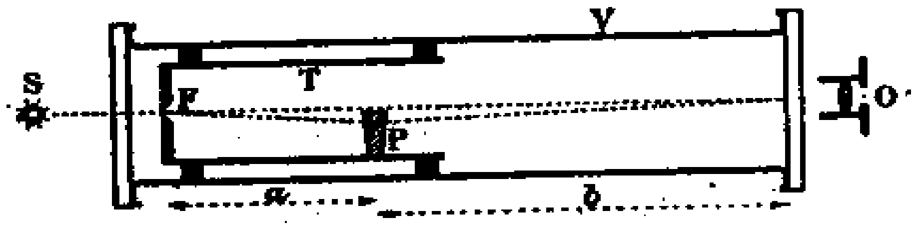

Figure 5b: A part of the device of Figure 5a: the slit F and the prism P (original drawing).

More precisely, if the light crossed the prism V, its former wavelength ? of the radiation would become:

$$l' = \frac{l}{1 + 2b\cos J} \tag{19}$$

where, as usual J is the angle of incidence of the light on the mirrors and ß= *v/c*.
The displacement of the fringes would therefore be:

$$e = (b - a)\left(\frac{1}{l} - \frac{1}{l'}\right) \tag{20}$$

where a is the segment PO and b is the segment FO.

The expected value of the displacement was 0.26 fringes between the cases of presence/absence of the prism V, and the experimental apparatus could reveal a displacement of 0.2 fringes, Majorana did not observe any displacement and from this he inferred a further confirmation -in the described experimental conditions- of the constancy of the speed of light. “These researches again had to rejection of the ballistic theory of the light.

Nevertheless ... I see that the light coming from (the mirrors) ... is forced to pass through the slit.

While this fact induces the phenomenon of diffraction according to the classical theory, it could allow further hypotheses, more or less simple and more or less reasonable, to support a ballistic theory. But we are not going to discuss them now"[18].

From these words it is clear that Majorana was not yet convinced, but his alternative hypotheses were not clearly stated, while his researches on the special theory of relativity will be resumed with new conjectures after the Second World War

His method of experimental research must be appreciated because of its originality and elegance, in addition to a high level of integrity and intellectual rectitude which led him, even in contrast with his initial belief, to consider his experimental results as they actually were: a proof of the validity of Einstein's postulate of the constancy of the speed of light.

They were some of the most original experimental confirmations of this postulate, as many others scientists admitted. Among others, we quote the words of Prof. Eligio Perucca: "The results obtained by Majorana in Turin from his two experiments are two of the most accurate experimental proofs of the validity of the second principle of the special theory of relativity. The physicist Jeans considered them as irrefutable proofs of Einstein's relativity. And such they have to be considered in the history of Physics"[3].

The Research About the Gravitational Absorption

"In a previous work on the influence of the motion of a light source of a mirror on the propagation of the light I expressed the conjecture that among the unknown causes that can influence the phenomenon there could be also the Earth's gravitational field"[19]. In this why Majorana expresses the motivation of the researches about the gravitational absorption which he started in Turin at the beginning of 1918 with complex experimental apparatus, which he has continuously improved in the subsequent experiments both in Turin and, later, in Bologna. Let us consider his own words in describing the transition to the new research: "I suspended the research about relativity in 1918 (I resumed it many times later) to start with a probably more complicated research, which was not pursued by any other physicist, at that time. Thinking about the incompleteness of our knowledge about the real nature of the force of gravitation ... and the idea of attributing to the cosmic ether (which has been banned by modern theories) the transmission of that force being inadequate, I decided to investigate if it could be somehow weakened by passing through (the matter)"[6]: Majorana's interest towards an investigation like this was caused not only by the fact that the gravitational field could be one of the causes which could influence the propagation of the light but also by some considerations about the origin of the energy of the stars and, particularly, of the Sun.

In fact, Majorana wrote that the hypothesis that the heat of the Sun could come from the contraction of the star was already unacceptable at that time: the age of the Sun which resulted from this hypothesis was of 50 million years only, an insufficient value "for geologists and naturalists"[20]. Other kinds of phenomena (which Majorana globally called radiative [20]) were not adequately known to ground any estimate upon them. While re-examining of the law of gravitation Majorana was induced to give an answer to this problem. He started analyzing Newton's law, underlining the independence of gravitation on the matter through which the gravitation propagated. This was a different behaviour with respect to other phenomena: "Among all the known physical laws, the universal law of gravitation seems to be the most perfect, due to its simplicity: the direct proportionality to the masses and the inverse proportionality to the square of distance (...). One of the most special characteristics of this law is that it does not depend in any way on the nature of the medium. As we know, all the natural actions ... reveal themselves in a different way according to the underlying medium: such are mechanical actions (propagation of shocks or vibrations or a simple pressure through a material medium), calorific, electrical, electromagnetic, luminous, cathodic rays, etc. In all these cases, the nature of medium (be it material or constituted by a hypothetical ether) has a main importance on the phenomena; if the medium changes the speed of propagation and the intensity of the phenomena undergo a variation, sometimes conspicuously.(...) As to the gravitation, nothing like this has ever been observed.(...) Surely, after the *actio in distans* of Newton's disciples (not Newton's, who never admitted it) was put among the absurdities, all the people who cultivate an interesting physics do think of the finiteness of such a velocity..."[19].

Majorana went on considering two possible hypotheses. "There are two different points of view from which the whole problem may be considered. The first can be extracted from the analysis of the attractive electrical and magnetic phenomena: in such cases one speaks of *permeability*. This is peculiar to the matter forming the medium, and determines the intensity of the force between two electrical or magnetic masses; the value of the force in a vacuum must be multiplied by a constant factor (the inverse of the permeability) to obtain its value within the medium.

As this is true for any value of the thickness of the medium, we can infer that the phenomenon of the electrical and magnetic permeability can be observed even for very small distances between the masses. To investigate the second aspect, we must consider another kind of phenomena, where the absorption of actions-in-distance occurs. The emitted energy (such as acoustic waves, light, cathodic particles, etc.) usually weakens not only according to the inverse square of the distance law (analogous to Newton's law) but also due to the fact that the medium progressively absorbs a part of it. In that case, it is often difficult, dealing with small thickness of the medium, to observe the weakening of the action. In the same way the air, transparent if small layers are considered, does conspicuously weaken the sunlight if its thickness becomes of many kilometres. The law underlying this absorption is not linear, but contains an exponential factor, variable with the thickness of the medium (...) it seems more likely, as to the gravitation, that a feature of the medium exists which can be defined *as the absorbing power* rather than *permeability* (...)"[19].

Majorana first reviewed many confirmations (Austin and Thwing (1897), Erisman (1908), Laager (1904) of the correctness of Newton's law (one part out of 100, 1200, 15000, respectively). Nevertheless, he was not satisfied even by the best confirmation among those, as he said that the performed experiments had never taken into account sufficiently great masses (for example planetary masses) and that in the astronomical measures only the "apparent masses" could have entered, not the "actual masses". Thus Majorana focused on the existence of an absorbing power of the matter with respect to gravitation. According to him, this would have two consequences:

1. Apparent decrease in the mass;
2. Equivalence of the gravitational phenomenon to propagation or a continuous transmission of energy in distance.

The first point introduced the concept of *apparent mass*: this was the mass with which a finite body interacted with other bodies according to the gravity. Thus, the apparent mass was the mass that entered the Newton's law. The most external particles of the body shielded the inner particles, giving rise to the effect of gravitational absorption.

In introducing the hypothesis of the gravitational absorption, Majorana quoted some of his predecessors and particularly Poincaré [19], who had used this hypothesis to eliminate the contradictions of Arrhenius' theory.

> Pour M. Arrhenius, le monde est infini et les astres y sont distribués d'une façon sensiblement uniforme; si nos télescopes semblent assigner des limites à l'Univers, c'est parce qu'ils sont trop faibles, et que la lumière qui nous vient des soleils les plus éloignés est absorbée en route. On a fait à

> cette hypothèse une double objection. D'une part, si la densité des etoiles est constante dans tout l'espace, leur lumière totalisée devrait donner au Ciel entier l'eclat même du Soleil. Cela serait vrai si le vide interstellaire laissait paisser toute la lumière qui la traverse sans en rien garder, de sorte que l'éclat apparent d'un astre varierait en raison inverse du carré de la distance. Il suffit, pour échapper à cette difficulté, de supposer que le milieu qui séparé les étoiles est absorbant; il peut d'ailleurs l'etre trés peu. L'autre objection, c'est que l'attraction newtonienne serait infinie ou indéterminéé; pour nous tirer d'affaire, il nous faut alors supposer que la loi de Newton n'est pas rigoureusement exacte, et que la gravitation subit une sorte d'absorption,se traduisant par un facteur exceptionnel.[6]

Then Majorana went on examination arguments in favour or against the existence of the "apparent mass" especially considering the Sun, which seemed to have a mass of $2x10^{33}$g and an average density of 1.41 grams per cubic centimetre.

Majorana observed that the density was likely to vary within the Sun: according to some theories he quoted, at the centre of the Sun the density could have been between 28 and $31\,gcm^{-3}$. If the hypothesis of the apparent mass held, it would have been reasonable to suppose an actual value of the solar mass greater than 2×10^{33}g: in such a case it would have been necessary to imagine a value of the internal density greater than the average estimated value.

The second consequence leads to hypotheses concerning the real nature of the gravitation. Majorana conjectured that an energy flux ("gravitational flux") may have originated from the matter and, upon striking other matter, could determine the gravitational force, even if with an unknown mechanism.

Moreover, the flux was partially absorbed by the matter itself. Majorana conjectured that the absorbed flux might be transformed into thermal energy: "the matter heats in presence of other matter"[19]. Coming back to the problem of the origin of the solar heat previously mentioned, Majorana thought it was reasonable to assume that it could come from a sort of unknown energetic transformation, as the conversion of the flux of gravitational energy into heat. Such a hypothesis could explain both the absence of dark stars and the origin of the solar heat.

Majorana devoted great efforts to this research, and performed four experiments: the first was carried on in Turin in 1918-19 and the others in Bologna in the 1919-20 (the second) and in 1921-22 (the third and the fourth)[7]. After the second World War Majorana worked again on gravitational absorption and on the relationship between gravitational and inertial mass [31], [32]; but his interest for gravitational absorption was then mainly speculative.

In this paper we are mainly concerned with the experimental researches which Majorana performed during the Twenties. In this experiment his goal was always to determine the variation of weight of a mass weighted in different conditions, which is with or without a shield made of a much greater mass than the one to weigh. The twofold measure of this mass in two different conditions should demonstrate the existence of a screening action due to the surrounding mass. Quantitatively speaking, supposing that the shielding mass M is a sphere of radius r and that the mass to be weighted m is put at the centre of it, then the problem is to determine h in the formula:

$$m_a = m_v e^{-hJr} \qquad (21)$$

where J is the density of M and m_a m_v, are the apparent and the true mass of m, respectively.

Clearly, to reveal the absorption it was necessary to operate with a high density material: lead and mercury (J = 11.34 e J = 13.56 gcm^{-3}, respectively) seemed to be reasonable candidates. By theoretical considerations about the apparent solar mass Majorana had previously estimated that the order of magnitude of h should have been an upper bound of $10^{-11} cm^2 g^{-1}$; thus if r is about ten centimetres, the product h J r has the order of 10^{-9}.

We may therefore truncate to the first order the series expansion of the exponential in (21) and we can write:

$$\frac{m_a}{m_v} = e^{-hJr} \cong 1 - hJr \tag{22}$$

that is:

$$h = \frac{e}{m_v Jr} \tag{23}$$

where $e = m_v - m_a$ is the mass decrease due to the gravitational absorption: it is the quantity to be measured.

In the first experiment, which started in October 1918 and was completed in July 1919 Majorana employed a Rueprecht balance with a beam of 26 cm and about 1 kg of capacity (Figure 6). The mass m was a lead sphere with a diameter of 60 mm suspended to the balance by means of a brass wire enclosed in a glass tube: the mass was inside a spherical cavity surrounded by a wooden cylindrical vessel where Majorana could make flow in and out a mass of 104 kg of mercury.

He had to deal with enormous experimental difficulties, due to the smallness of the effect to be measured. First of all, he had to find the way of making a vacuum inside the glass vessel containing the system formed by the balance and the mass m; this was necessary because it was impossible to avoid small differences of temperature in the mercury, when it flowed in and out, and this in turn gave rise to small but significant variations of the buoyancy acting on m due to the presence of the air. Then Majorana had to make sure that the symmetry of the system formed by the sphere and the cylindrical vessel was enough to avoid any momentum acting on m.

The position of the beam of the balance could be determined through the displacement of a light ray reflected by a small mirror fixed to the beam; the displacement could be read on a graduated scale distant 12 m from the experimental apparatus. Majorana was even compelled to carefully select the kind of the electric light bulb employed to generate the light ray, as in some cases the white-hot filament underwent a displacement, giving rise to a displacement in the zero position of the balance. Another source of instability was given by even very small mechanical movements, which affected the building of the Institute itself due to the passage of carriages and cars in the adjacent streets. Thus Majorana decided to execute the experiments overnight or in the days of general strike, very frequent in July 1918-9. Finally, Majorana had to evaluate carefully the sensibility of the balance (which tended to change with and without charge) and the mechanical action on the floor exerted by the mercury entering the vessel: the floor sank approximately 2 mm and the weight of m was fictitiously increased due to the presence of the mercury. Majorana solved this problem with a total mechanical de-coupling between the balance and the vessel.

After repeated series of measures (some thousands of observations), Majorana obtained an experimental estimate for the gravitational absorption. He then examined all the possible sources of systematic errors, in order to evaluate their magnitude and to remove them from the final result. It was in this long and difficult process that Majorana showed his enormous skill as an experimenter, which allowed him to discover and evaluate very subtle effects. In fact, he had first to examine the gravitational force deriving from possible lack of symmetry between masses and the effect of the instability of the equilibrium position of the balance; in addition to this Majorana had to estimate the gravitational effect of the mercury on the various masses: this was complicated by the fact that the two different positions of the mercury during the experiment had to be taken into account.

Finally, combining all the corrections and evaluating in the most “pessimistic” way the effect of possible lack of symmetry between the masses, Majorana obtained:

$$e = (0.00097 \pm 0.00016)mg \tag{24}$$

and this led to the following estimate for h:

$$h = \frac{e}{m_v Jr} = \frac{9.7\times10^{-7}}{1274\times13{,}56\times8.4} = 6.68\times10^{-12}\,\frac{cm^2}{g} \tag{25}$$

where 1274 is the mass (in grams) of the sphere, $13.56\,gcm^{-3}$ is the density of the mercury and 8.4 is the thickness (in cm) of the shielding layer of mercury. Thus the 1274 g lead sphere seemed to loose a fraction of its weight given by:

$$\frac{m_{v-}m_a}{m_v} = \frac{9.7\times10^{-7}}{1274} = 7.6\times10^{-10} \tag{26}$$

Majorana thought that the result he had obtained confirmed his initial conjectures, and concluded: “The importance of this research is clear, and it does not seem to me that there can be found simple criticisms against it. In any case, as I my-self want to become completely sure of the result of my experiments, I declare it is my purpose to repeat them with better equipments”[19].

Thus, as soon as the first experiment was completed, with very interesting results, we can see Majorana already turning his mind to its confirmation with a new and better apparatus, which he began to build at the beginning of 1920.

The results of this further experiment of gravitational absorption were soon available and were published, together with the description of the employed apparatus, in a new series of papers presented to the Academy of Lincei [26], and in other papers published both in Italy and abroad[8].

To perform the second experiment Majorana employed a shielding mass made of lead of 9603 kg, about 92 times greater than the previous one (Fig. 7).

According to his theory he expected a variation of weight of 5/1000 mg, five times greater than the one obtained with the 104 kg shielding mass. The shape of this new shielding mass was a cube with a side of 95 cm, subdivided into two identical parts resting on revolving supports: so, the mass could be moved near or taken away from the sphere which in the first case could be put in a spherical cavity at the centre of the cube.

Majorana had to take into account the mechanical strains undergone by the building, as a consequence of moving such a great mass: these strains implied also a rotation of the plane where the central knife edge of the balance rested.

With respect to the first experiment he discovered and accurately evaluated an additional source of error which was usually neglected and derived from the curvature of the edge of the knife: only in an ideal case the place of contact between the knife and the plane is a geometrical straight line. This effect impacted, as Majorana demonstrated, the position of the centre of oscillation of the balance and its sensibility.

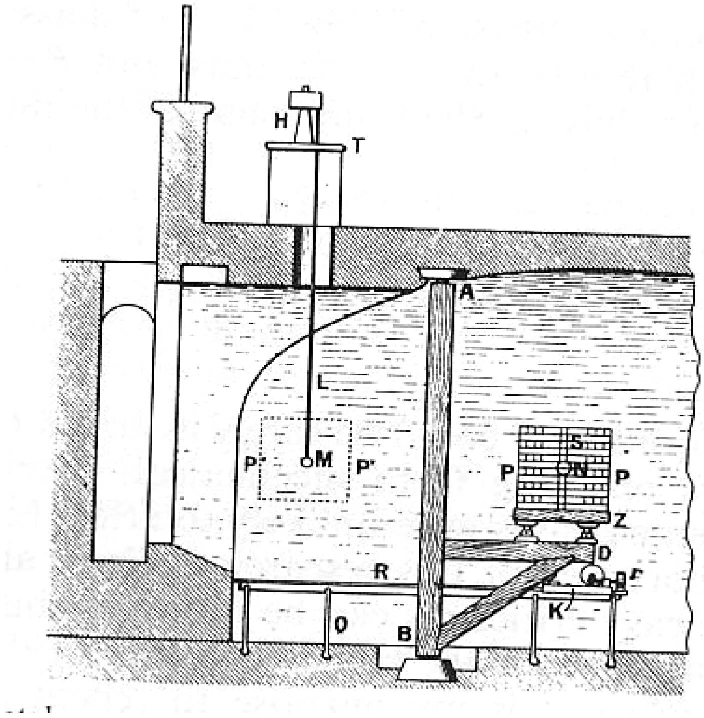

Fig. 7. Experimental apparatus (1920) for the research about gravitational absoption. Original drawing.

Taking into account this error source, which was likely to be present also in the previous experiment, Majorana obtained a new estimate for *h*:

$$h = 2.28\times10^{-12}\,\frac{cm^2}{g} \tag{27}$$

a value of the same order of magnitude but significantly smaller.

Nevertheless Majorana thought he had taken into account by that time all the possible sources of errors, and when he completed the second experiment, in 1921, he strongly felt he had discovered a real effect of gravitational absorption: "The most subtle experimental researches I tried to describe precisely in the last papers and in the previous ones, base themselves upon a new concept of one of the most important natural phenomena. Somebody may be induced to think that my approach is totally arbitrary; nevertheless I think it has been logical.

If, on the one hand, the hypotheses I proposed with every caution are surely bold, on the other hand they allowed me to undertake experimental researches which otherwise would have never been attempted. Now, the experimental research represents the real foundation of Science, and its results are facts which in any case enrich our patrimony of scientific knowledge. As to my researches, one can also leave aside the *a-priori* theories I proposed, taking for good the conclusion that *a mass appears lighter when surrounded by other masses* (Majorana's italics)"[26].

The experiments performed by Majorana gave rise to interest and criticisms by the international scientific community. In July 1921 Albert Michelson asked Majorana the permission to repeat the experiment in Pasadena laboratories, and this contributed to increase the importance of the researches and the perseverance of the author:

> Dear Professor Majorana,
>
> I have been very much interested in your very important work on gravitational shielding and it seems to me you have neglected no essential factor.
>
> I have been requested by Dr.G.E.Hale to undertake a repetition of this research at his laboratory in Pasadena Ca. But, before giving my consent, I am writing to know if you would have any objection - and I trust you will not hesitate to express yourself on the subject with entire freedom - and I can assure you that I should not think of intruding in a field which you have made your own unless I have your approval.
>
> Very sincerely yours, A.A. Michelson. [25]

The permission was given, but it had no practical consequences. Prof. Perucca mentioned this fact to stress the experimental ability of Majorana: “In any case, in several papers by Majorana, all included in the Proceedings of the Academy of Lincei, we cannot avoid admiring such an experimental technique and a critical examination of the results which I do not think it has ever achieved by many scientists; in the same way (Majorana) will show a rare ability in defending himself against the doubts and the scepticism expressed by many people. It is worth reading even only one paper about the subject, i.e. the one containing a talk about the gravitational absorption he gave in 1930 in Paris on invitation of the French Society of Physics; one can extract from this paper a general view of the work devoted by Majorana to this research and to the refutation of the doubts of other scientists about this subject. Those doubts can be proposed both on the ground of some astronomical consequences of gravitational absorption and even from some experimental conclusions. But among these doubts should not be mentioned Michelson’s request to Majorana of repeating the experience at Mount Wilson and the subsequent abandonment of this programme. Did Michelson not go on with the experiment either because he was convinced it was meaningless or because he knew he should devote a great deal of time and resources to reach or, better, to overcome the precision obtained by Majorana? It has been said in a malignant way that Majorana has merely checked the correctness of the Newton’s law with a degree of precision one thousand times greater than any other previous terrestrial experiment had achieved. And does this seem not enough to you?”[3].

In 1921 the astronomer H. N. Russell published a paper with some comment about Majorana’s theory [34]. Taking into account astronomical considerations he questioned the value and even the existence of the coefficient of absorption h measured by Majorana: according to his calculations, even if h did exist, its value could not be more than the 1/10000*th* part of the measured value, and this was due to the fact that he had not discovered any of those perturbations of the motion of planets which should have revealed themselves as a consequence of the phenomenon studied by Majorana. Also Eddington took an interest in the subject from the point of view of the relativity of the gravitational field [35]. According to Eddington, a body can absorb only the gravitational field relative to itself: a free falling body does not experience any gravitational effect and, therefore, does not absorb anything.

Now, the particles which form a planet can be regarded as free falling bodies and the solar gravitational field relative to them vanishes: we do not have absorption. This argument answered some of the Russell’s criticisms. As for the mercury in Majorana’s experiment, Eddington argued that it absorbed as it was not freely falling with respect to the Earth. Eddington thought that Majorana’s results together with the absence of any perturbation to the motion of the planets were a confirmation of the principle of equivalence. Nevertheless, he concluded that, besides this confirmation, the hypothesis by Majorana was untenable as a gravitational theory, because it was likely to violate some principles of conservation, as Russell had already conjectured [34], [35].

In addition to the mentioned researches Majorana performed some other experiments in 1921-22[29], which turned out to be in good agreement with his previous results. As in the first experiment, in his third attempt Majorana employed a relatively small shielding mass (about 180 kg), after realizing the difficulties of operating with very large masses [33]. Moreover, Majorana carefully avoided to employ ferromagnetic materials and tried to increase greatly the sensibility of his apparatus by means of multiple reflections of the ray reflected by the mirror fixed to the beam of the balance. In this experiment, Majorana obtained an estimate for h of $2.8\times10^{-12}cm^2g^{-1}$, much closer to the second than to the first estimate he had obtained. In his fourth experiment Majorana employed again the mercury as absorbing material [33] using an apparatus very similar to the one he had employed in the first experiment. Majorana highly prized his previous experiences and carefully avoided to use ferromagnetic materials; moreover he adopted some solutions already employed in the second experiment. Even with this apparatus Majorana did not obtain conclusive results about the phenomenon, but succeeded anyway in confirming at least quantitatively his previous results, by evidencing an effect of gravitational absorption.

The idea of an absorption of the gravity by the particles of matter never left him for the rest of his scientific life, and he would have resumed this topic in a series of papers published between the end of '40s and the beginning of '50s [31],[32], but in a manner more speculative than experimental: therefore, we will not consider them in this paper. In particular, in the paper of April 13th 1957 we can read: "...the only reasonable hypothesis (if we discard the one concerning Lesage's mysterious ultra-mundane particles) to formulate a theory of gravitation is that any kind of matter emits a sort of peculiar particles, which I call *gravitons*: it is logical to suppose that a part of them will be absorbed by the attracted matter. If not, we would have an effect (the attraction) without any cause. My experiments seem to confirm this hypothesis. But unfortunately, in spite of the great logical exactness on which they are founded, and besides the interested comments made by some important scientist some time ago, they are almost forgotten today, and nobody has ever thought of resuming and completing them later"[31]. On 31st of July of the same year Majorana died in Rieti.

Conclusions

In this paper we have dealt with the personality of an important experimental Italian physicist of the 20th century, and we have outlined his work in two of the topics he was mostly interested in throughout his long scientific life. Even if briefly outlined, the resulting profile is the one of a scientist who was very careful, meticulous, self-confident with a great imagination as to planning, performing and evaluating an experiment, and, most important, deeply convinced of the fundamental importance that experiments had for research in physics. Quirino Majorana was so bold as to tackle difficult experiments, which would today require teams of tens of experts, and he was totally alone! And, moreover, without adequate financial support. He heavily paid for his boldness. Nevertheless, he managed to tackle his researches with unpretentiousness, integrity, bravery, with a continuous zeal all his life.

His figure is not as famous as it could have been if his experiments had pointed out with certainty some contradictions in the special theory of relativity and in the law of gravitation: rather, the results he obtained concerning the second postulate of the special relativity must be regarded as some of the most perfect confirmations of it. Nevertheless, it seems logical to say that Majorana and his opponents had very different ways of looking at the problem: on the one hand the experimental data to be accepted in any case, on the other the rejection of those data which indicated the presence of a feeble effect, which was in disagreement with the current theories.

Keeping in mind that in the scientific world the topics considered as the most important strongly influence the common idea of experimental science and that the teaching of science does not sometimes seem to fully exploit the correlation between theory and experiment, it is instructive to mention a scientist for whom this correlation was the centre of his scientific creed: Quirino Majorana, experimental physicist. Experimental science will surely regard him as one of its most brilliant and coherent sons.

Notes

[1] We thank our friend Erasmo Recami for kindly allowing us to read these very interesting documents, provided to him and to Franco Bassani by Quirino Majorana's daughter, Silvia Toniolo Majorana. Thanks to all of them and to Helen Turner, for her revision of our English text.

[2] These sentences are quoted from a letter which Quirino declared he wanted to keep a copy of, dated Rieti, August 22nd 1936 XIV. The letter concerned some research of photo-resistency in thin laminas (our translation).

[3] See, in the bibliography listed in reference [1], the papers quote at the points 105...111 and 114...120.

[4] It must be remembered that the Nobel prize was assigned to Einstein in 1921 for "his contributions to mathematical physics and especially for his discovery of the law of the photoelectric effect" (L. Motz, J.H. Weaver, *The Story of Physics*, Plenum Press, New York, 1989, p. 249); the theory of relativity was not explicitly mentioned.

[5] It must be noted that, in the following formulas, c and v can indicate both the speeds of the light and of the source, respectively, and the distances they run along in a second. Moreover, the symbols n and n', indicate the numbers of waves emitted in the time unity, that is the frequencies.

[6] H. Poincard': *Leçons sur les hypothèses cosmogoniques*, Paris, 1911. Préface, p. XXI-XXII.

[7] The results of these experiments are reported in references [19], [20], [21], [22], [23], [24], [25], [26], [27],[28], [29], [30].

[8] Reference [27] e [28]. It must be remarked that the results of the first experiments had been published in the *Philosophical Magazine* (reference 23]) and in the *Comptes Rendus* of the Paris Academy of Sciences (reference [21] and [22]). Finally, Majorana would publish in the *Journal de Physique et le Radium* of 1930 a review of his experience (reference [33]).

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