Majorana's Experiments on Gravitational Absorption

Roberto de Andrade Martins*

Around 1920 the Italian physicist Quirino Majorana claimed that he had measured an effect that may be called "gravitational absorption": the reduction of the gravitational attraction between two bodies when one of them is enclosed inside a thick material shell. He published the results of experiments where a test body was surrounded either by mercury or by lead, and in both cases he detected a weight reduction of about one part in 10^9. This paper presents the theory underlying Majorana's work, together with a detailed description of his experiments.

1. Introduction

Many theories attempting to explain gravitation have been proposed since the 17th century (Woodward, 1972). A large proportion of these attempts can be described as *kinetic theories of gravitation* (Taylor, 1876), by their analogy to the kinetic theory of gases. They assume that material bodies do not interact by direct action-at-a-distance, but by acting and being acted upon by particles (or waves) travelling through space. The analysis of these mechanical models led to the conclusion that they would be unable to explain gravitation if only perfectly elastic collisions existed between the particles (or waves) and matter. Hence, all useful kinetic theories of gravitation must assume that matter absorbs or somehow changes these particles or waves.

Although kinetic theories of gravitation were very popular in the 19th century, nobody had endeavoured to detect the absorption of gravitation up to the 1890's. In 1897 Austin and Thwing made the first known experimental test of the existence of a change of gravitational force due to interposed matter using a torsion balance (Austin and Thwing, 1897). No effect was detected. Several other similar experiments were attempted in the early 20th century, but no clear positive result was reported until the publication of Majorana's research (Martins, 1999). In 1919 this Italian physicist announced that he had been able to observe a decrease of the weight of a body when it was enclosed within a thick shield of matter.

This paper will describe Majorana's ideas and experiments on gravitation, with special emphasis on his measurements of gravitational absorption, as they seem the most careful studies on this subject that were ever made.†

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† Information about some recent attempts to detect gravitational absorption may be found in George Gillies' very complete surveys of experimental gravitation (Gillies 1987, 1990, 1997; see also the paper by Unnikrishnan & Gillies in this volume).

Fig. 1 – The Italian physicist Quirino Majorana (1871-1957). Photograph copyright by Maria Majorana & Erasmo Recami. Reproduction kindly authorised by Erasmo Recami.

2. Majorana's Hypothesis

Quirino Majorana (1871-1957)* was an Italian experimental physicist who devoted many years of his active life to the search for gravitational absorption. Nowadays Majorana's better known researches are those related to the second principle of the special theory of relativity. He attempted to detect changes in the speed of light emitted (or reflected) by moving bodies, but contrary to his expectations he confirmed that the speed of light is independent of the speed of its source. As this result was the opposite of what he intended to prove, it gives nice evidence that Majorana was a careful experimenter and not one of those scientists who always find what they want to find.

Majorana published the details of his work in several articles that appeared in Italian scientific journals (Majorana, 1918-19, 1919-20a, 1919-20b, 1921-22). He also published shorter accounts of his researches in French (Majorana, 1919a, 1919b, 1921) and in English (Majorana, 1920).

In his first paper on gravitation Majorana presented the speculations that led him to his experimental work (Majorana, 1918-19). His point of departure was a concern with the energy of the stars. At that time, with nuclear physics still in its infancy, it was difficult to reconcile the long duration of the Sun required by geology and evolution theory with the largest possible duration allowed by physical theories. Majorana conjectured that gravitation was due to the flow of gravitational energy from all bodies to their surrounding space. This outward flow of gravitational energy necessarily required some kind of gradual transformation of matter, analogous to radioactivity, but Majorana

* There are two general accounts of Majorana's scientific contributions, one of them written by Majorana himself (Majorana, 1941 and Perucca, 1958). Quirino Majorana should not be misidentified with his nephew, the nuclear physicist Ettore Majorana. English-speaking readers should be warned that "Quirino" is pronounced as Kweereeno, and that the "j" in "Majorana" should be pronounced as "y" in "yes," with emphasis at the "ri" of "Quirino" and "ra" of "Majorana."

supposed that this transformation was very slow and difficult to detect. He also supposed that matter is not transparent to the gravitational flux. Gravitational energy would be absorbed by matter and transformed into heat. All bodies would therefore be subject to a spontaneous heating effect. This effect would be noticeable only for very large bodies, since the generation of heat from a body would be proportional to its volume, while the emission of heat would be proportional to its surface area. According to Majorana, this absorption and heating effect would account for stellar energy.*

Majorana was not altogether clear about the mechanism of gravitation he envisaged. Sometimes he referred to a "gravitational energy flux," sometimes to "particles," and, in his later years, he called these particles "gravitons." He remarked that his "particles" would have strange properties, because when they hit matter they must produce a backward impulse.

Majorana was not a theoretician. His main work, throughout his life, was that of an experimental physicist; so he was not much concerned about the precise mechanism of gravitational absorption. In the absence of any theoretical framework, he attempted to compute some of the consequences of the hypothesis and to test it by delicate experiments.

In order to test his general assumption, Majorana tried to detect a reduction of weight of a lead ball (1 kg) when it was surrounded by 100 kg of liquid mercury. The preliminary experiments, however, produced a result directly opposite to his hypothesis: there seemed to occur an *increase* of 1/30,000,000 of the weight of the test body (Majorana, 1918-19, p. 668).

After the preliminary test he began to study some theoretical features of his hypothesis. First, by taking into account some previous experiments, Majorana gave up the possibility of anything like a gravitational permeability. Analogy with electromagnetic phenomena pointed out that an effect of this kind should be observable even with a low sensitivity and thin slices of matter. Hence, Majorana suggested that only the search for very weak gravitational absorption effects could possibly give any positive result. In order to plan an improved experimental setup, he tried to evaluate the upper order of magnitude of the effect that was to be searched for. This led him to develop a quantitative theory of gravitational absorption (Majorana, 1919-20a, 1919-20b).

Let us compute the gravitational absorption due to a homogeneous material medium. According to the simplest absorption hypothesis, a corpuscle of mass M placed in this medium would produce at the distance r a gravitational field g equal to

$$g = GMr^{-2}e^{-Hr}, \tag{2.1}$$

where H is the characteristic gravitational absorption constant of the medium. Majorana assumed that H does not depend on the chemical composition of the medium, but that it would be proportional to its density: $H = hd$. Assuming that

* This idea was not developed in Majorana's early works. It was discussed, however, many years later (Majorana, 1954).

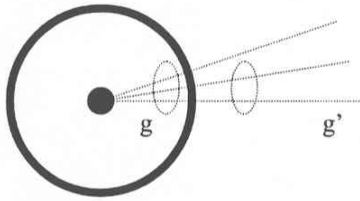


Fig. 2 – When an attracting mass is inside a spherical shell, the gravitational absorption by the shield would produce a smaller gravitational field *g'* outside the shell.

a large sphere of matter would have a non-negligible self-absorption of gravitation, Majorana computed its external field.

3. External Gravitational Field Produced by a Large Body

This very same hypothesis had been dealt with by Laplace one century earlier, and its consequences had been discussed by Henri Poincaré in his lectures on gravitation in the years 1906-1907. Poincaré's work was only published much later (Poincaré, 1953), however, and so Majorana had to compute by himself the consequences of his hypothesis. In what follows, some features of Poincaré's derivation will be used instead of Majorana's, because they are easier to follow and clearer. The final results will agree with Majorana's, however.

Suppose a very small but massive body is enclosed in the centre of a spherical shell (Fig. 2). Let us neglect the self-absorption of gravitation by the mass comprising the shell. Inside the shell, the value of the gravitational field is

$$g = GMr^{-2} \tag{3.1}$$

and outside the shield the field is

$$g' = GMr^{-2}e^{-HL}, \tag{3.2}$$

where L is the thickness of the shield. The force decreases but does not change its direction. Both inside and outside the shield the direction of the gravitational field is radial, and in both cases the force varies as the inverse square of the distance to the attracting body. In both regions the divergence of the gravitational field $\vec{\nabla} \cdot \vec{g}$ is null, because there are no sources or sinks of the gravitational field. The gravitational flux through a closed surface which does not contain the body is also null.

The total gravitational flux Φ traversing a closed surface inside the spherical shell and containing the massive body is

$$\Phi = 4\pi r^2 g = 4\pi GM, \tag{3.3}$$

and the total flux Φ' traversing a closed surface outside the spherical shell and containing the massive body is

$$\Phi' = 4\pi r^2 g' = 4\pi GMe^{-HL}. \tag{3.4}$$

That is, both inside and outside the shield, Gauss' law for gravitation holds, although the total flux has different values inside and outside the shield (Fig. 3).

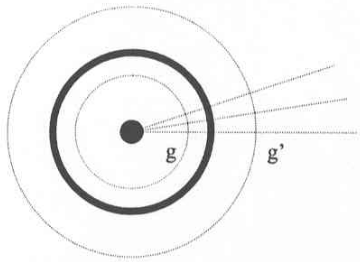


Fig. 3 – If an attracting mass is inside a spherical shell, the total gravitational flux across closed surfaces containing that body will be proportional to its effective gravitational mass. However, the gravitational absorption produced by the shield will decrease the external gravitational field *g'* produced by the inner body, and hence its external gravitational flux will be smaller than its gravitational flux inside the shell.

Now suppose we have a massive sphere with self-absorption of gravitation (Fig. 4). If the density of this body has spherical symmetry, then the gravitational field outside the sphere must have a radial direction everywhere, according to Curie's law of symmetry, and the intensity of the gravitational field is a function of the distance r to the centre only. Outside the sphere there are no sources or sinks of the gravitational field, and therefore the divergence of the gravitational field is null, *i.e.*, $\vec{\nabla} \cdot \vec{g} = 0$. Therefore Gauss' law applies to the exterior gravitational field, and the total gravitational flux Φ'' across a spherical surface will be the same whatever the radius r of the spherical surface, that is,

$$\Phi'' = 4\pi\, r^2 g'' . \tag{3.5}$$

Outside the massive sphere the gravitational field varies as the inverse square of the distance r to the centre of the sphere,

$$g'' = \frac{\Phi''}{4\pi\, r^2} . \tag{3.6}$$

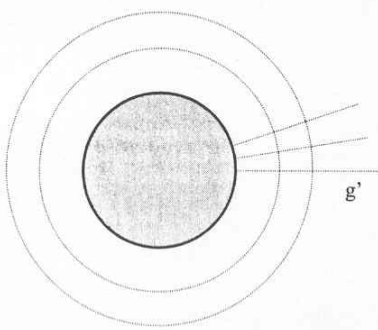


Fig. 4 – When gravitational absorption is taken into account, the external field produced by a large attracting spherical body would be diminished by self-absorption. However, outside the body there is no absorption and the total gravitational flux across any closed surface containing this body will have the same value, whatever its distance from the attracting body. Accordingly, the gravitational field *g'* will obey the inverse square law.

Therefore, outside the sphere Newton's law of gravitation is valid, but instead of the real mass of the sphere $M = \int \rho\, dV$ it is necessary to take into account a smaller effective (or apparent) gravitational mass $M' < M$.*

* This was a simple and clear result, but in 1948 Giuseppe Armellini published a paper where he arrived at a different result (Armellini, 1948). He claimed that the force produced by a spherical body, taking into account its self-absorption of gravitation, would obey a different law: $g = GM'/(r - \varepsilon)^2$, where ε would represent the distance between the geometrical centre of the body and its effective force

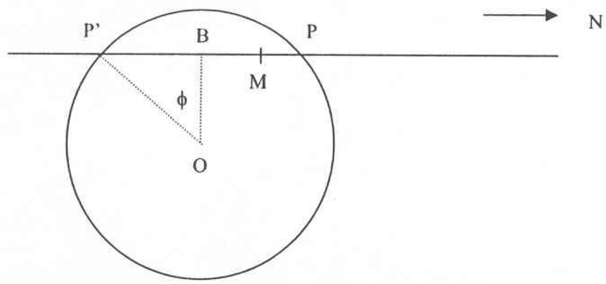


Fig. 5 – In order to compute the effective gravitational mass of a large homogeneous spherical body, following Poincaré's derivation, one computes the mean effective density relative to a distant point N, along different straight lines drawn through the sphere.

In order to use Newton's law of gravitation, now taking into account this effect of self-absorption of gravitation, we need to know the "apparent mass" of a large body. Let us compute its value in the case of a homogeneous sphere.

Consider a homogeneous sphere of radius R and real density ρ, with an absorption coefficient H (Fig. 5). It is easier to compute its gravitational effect relative to a distant point, as the result obtained for its apparent gravitational mass can then be applied to compute its field at any distance from its centre. The apparent mass can be calculated relative to a distant point using a set of parallel lines that cut the sphere, computing the apparent density ρ' of each point inside the sphere and then integrating over the whole sphere. The following symbols will be used (Fig. 5):

$$\mathrm{OP} = \mathrm{OP'} = R$$
$$\mathrm{BM} = \mathrm{y}$$
$$\mathrm{MP} = q - y$$
$$\mathrm{OB} = x = R \cos \phi$$
$$\mathrm{PB} = \mathrm{P'B} = q = R \sin \phi$$

Relative to a distant point N, the apparent density ρ' at point M will be:

$$\rho' = \rho\, e^{-H(q-y)}. \qquad (3.7)$$

Therefore, the mean apparent density ρ'' along the line PP' of length $2q$ will be:

$$\rho'' = \frac{\rho}{2q}\int_{-q}^{+q} e^{-H(q-y)}dy = \frac{\rho}{2qH}\left(1 - e^{-2Hq}\right). \qquad (3.8)$$

Now, take a cylindrical sheet of radius $x = OB$ and thickness dx. Its mean density is ρ'' and its volume is equal to $4\pi\, q\, x\, dx$. Therefore its mass is:

centre. He then proved that, once this law is accepted, this would produce a perihelion precession. However, Armellini's law of force is wrong, as it is incompatible with the above proof that the gravitational field outside the sphere must obey the simple law $g = GM'/r^2$. The main error in Armellini's derivation was the use of some equations of classical mechanics that do no apply to this case.

$$dm' = \frac{2\pi\rho}{H} e^{-2Hq}\, xdx\,. \tag{3.9}$$

Replacing x by $R \cos\phi$ and q by $R \sin\phi$, and integrating, we obtain the apparent mass of the whole sphere:

$$M' = \frac{2\pi R^2 \rho}{H} \int_0^{\pi/2} \left(1 - e^{-2HR\sin\phi}\right) \cos\phi \, \sin\phi \, d\phi\,. \tag{3.10}$$

Integration is straightforward, and the final result is:

$$M' = \frac{2\pi R^2 \rho}{H} \left(\frac{1}{2} + \frac{e^{-2HR}}{2HR} + \frac{e^{-2HR} - 1}{4H^2R^2} \right). \tag{3.11}$$

Notice that Poincaré computed the apparent mass of the sphere taking into account the gravitational field that would be observed at a distant point. However, as the external field of the sphere obeys the same equation as Newton's law of gravitation (with a reduced mass), the result can be applied to compute the field at any distance from the sphere.

Taking the limit when $H \rightarrow 0$, one obtains the real mass $M = (4/3)\pi R^3 \rho$. When the absorption is small ($HR << 1$) but not negligible, the apparent mass of the sphere will be approximately:

$$M' = \frac{4\pi R^3 \rho}{3} \left(1 - \frac{3HR}{4} \right). \tag{3.12}$$

Majorana computed the absorption effect using a different mathematical method, but he obtained completely equivalent results. He introduced the concept of apparent active gravitational mass M_a different from the "real" mass $M_v = (4/3)\pi R^3 \rho$. He represented the ratio between apparent mass and true mass by ψ (that is, $M_a = \psi M_v$) and computed this factor for a homogeneous sphere*. He found

$$\psi = \frac{3}{4} \left\{ \frac{1}{RH} - \frac{1}{2(RH)^3} + \left[\frac{1}{(RH)^2} + \frac{1}{2(RH)^3} \right] e^{-2HR} \right\}. \tag{3.13}$$

This result is exactly equivalent to Poincaré's equation (3.11), as may be easily checked.

4. The Upper Limit of the Absorption Constant

As described above, Majorana supposed that the absorption constant H was proportional to the true density of matter: $H = h\rho_v$. The parameter h was supposed to be a universal constant.

Let us now apply these ideas to the Sun. Its effective or apparent active gravitational mass is known from its effect upon the planets. From its effective

* Majorana experienced some difficulties in deriving this result, and in one of his papers he presented a different result (Majorana, 1919/20b, p. 314). The equation presented here was published in his other articles (Majorana, 1919/20 a, p. 75; Majorana 1919/20 b, p. 420; Majorana 1919a, p. 648; Majorana 1920, p. 494).

gravitational mass, it is easy to compute that the effective mean density of the Sun is about 1.41 g cm^{-3}. If there is gravitational absorption, the real mean density of the Sun must be greater than the above value.

Although the Sun is not homogeneous, Majorana applied the model of the homogeneous sphere to this case. Using values of true density larger than 1.41 g cm^{-3} he computed by successive approximations the corresponding values of *h*:

ρ_V (g cm^{-3})	ρ_a / ρ_V	h (cm^2 g^{-1})
1.41	1.000	0
2.0	0.705	3.81×10^{-12}
5.0	0.281	7.08×10^{-12}
10	0.141	7.49×10^{-12}
15	0.094	7.63×10^{-12}
20	0.070	7.64×10^{-12}

This computation led to an unexpected result: if the true density of the Sun is supposed to increase and to go to infinity, the absorption constant *h* approaches a finite value: 7.65×10^{-12} cm^2 g^{-1}. That is, if a simple model (homogeneous density) is applied to the Sun, its known apparent active gravitational mass imposes an upper limit to the value of the constant of gravitational absorption. Of course, the Sun is not a homogeneous sphere. However, even with this simple model, it is remarkable that Majorana could reach an upper limit for the constant of gravitational absorption.

For a variation of the true density from 2 to 20 g cm^{-3} the absorption coefficient *h* remains always of the order of magnitude of about 10^{-11} cm^2 g^{-1}. Therefore it seems sufficient to suppose that the true density of the Sun is larger than its apparent density [of 1.41], in order to determine the order of magnitude of the "universal constant of absorption" *h*.* Majorana used this upper limit for the constant *h* to plan a suitable experimental test of the hypothesis, as will be shown below (Majorana, 1919-20b, p. 317).

5. Majorana's First Measurement

Could such a small effect be measured in a laboratory experiment? A simple computation will show that under laboratory conditions the effect would be very small indeed. As a first approximation, the gravitational force acting upon a body inside a spherical shell would undergo a relative reduction of about $hD\rho$, where D is the thickness of the shell. To compute the order of magnitude of the effect, we take ρ = 10 g cm^{-3} (lead, mercury), D = 10 cm and h = 10^{-11} cm^2 g^{-1}. The relative weight reduction would amount to 10^{-9} (*i.e.*, a reduction of about 1 μg for a 1 kg body). In order to *measure* such an effect, it

* This is not correct, of course. If the true density of the Sun is only slightly greater (say, 0.001%) than its apparent density, the constant of absorption would be much smaller than 10^{-12}.

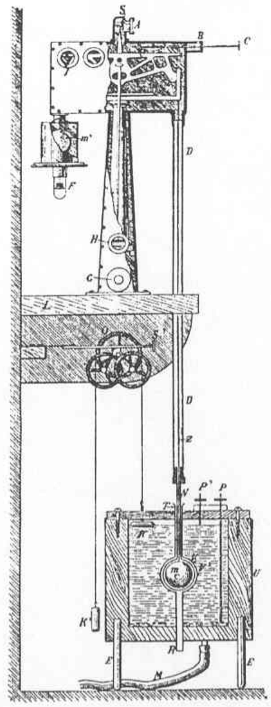


Fig. 6 – Majorana's first measurement of the coefficient of gravitational absorption employed a test body *m* attached to a sensitive balance. The test body could be enclosed by liquid mercury contained in a wood cylinder *U*.

would be necessary to attain a sensitivity at least 10 times better, and therefore it would be necessary to detect changes of 0.1 μ g in 1 kg (that is, 10^{-10}).*

No balance of that time could measure such a small change of weight. However, after several trials and improvements, Majorana adapted a system that had the required sensitivity. The experimental work was developed in the Physics Laboratory of the Turin Polytechnic, then directed by Majorana himself. In his papers Majorana provided a detailed description of his highly ingenious solutions for several experimental problems. It is relevant to grasp the main feature of the measurement method he used, since these experiments constitute the most important positive laboratory evidence for gravitational absorption ever obtained. The account provided below is as detailed as the limits imposed upon this paper will allow, but experimental physicists should consult the delightful original account, as it contains a wealth of relevant details and comments.

In these experiments, Majorana used the best available Rueprecht analytic balance, with several additional devices (Fig. 6). The balance and the test bodies were enclosed in a 5 mm thick brass vessel, where a vacuum was produced

* Of course, it is be possible to increase the thickness of the shield to produce a stronger effect, but other difficulties will arise, in that case.

to avoid any perturbation due to air currents, convection, buoyancy, *etc.* It was possible to manipulate the balance and the rider (of 10 mg) from outside (*C*). The oscillations of the balance were measured using a beam of light reflected by a concave mirror (*S*) at the top of the balance, through a strong glass wall (*A*). The mirror produced a sharp image of the filament of the electrical lamp at a distance of 12 m. In typical experiments, a deflection of 170 mm of the light spot corresponded to 1 mg, and it was possible to measure a displacement of 0.1 mm of the position of the light spot, corresponding to a weight change of 0.59 μ g.

Attached to the left side of the balance there was a 1.274 g sphere of lead (m'). Connected to the right side by a long brass wire (about 80 cm long) there was a second lead ball (m) of equal mass. It was enclosed in a hollow brass sphere (V') and this was included in another hollow brass sphere (V). The two shells did not touch each other. The second sphere could be surrounded by liquid mercury that was introduced in a strong wood cylindrical vessel (*U*). The balance and vessel were covered by a threefold thick cover made of camel hair to avoid changes of temperature. Measurements and control of the apparatus were made from another room, at a distance of 12 m from the balance, to avoid mechanical and thermal influences of the observer upon the apparatus.

No attempt was made to determine the exact weight of the test body. Instead of making two extremely precise measurements and then finding their difference, Majorana tried to observe *changes* of the weight of the test body when it was surrounded by mercury.

First, the system was carefully balanced and brought to equilibrium. The balance was never completely immobile, however, and the reflected light beam kept drifting during all experiments. Measurements were made when the drift of the spot was regular and slow (about 5 mm per hour). During the measurements, mercury was first introduced in the wooden vessel and then taken off, and any change of equilibrium of the balance was observed. The expectation was that the weight of the test body would show a small reduction when mercury was put around it, and then the weight should return to its initial value when mercury was withdrawn from the wood cylinder.

The balance was so sensitive that the best measurements could only be made in the first hours after midnight (from 1:30 to 4:30 a.m.), to avoid vibrations due to street traffic. Smaller vibrations would blur the reflected spot, making precise measurement impossible; larger vibrations due to the passage of trams or trucks would occasionally produce oscillations of the light spot of a few mm. The finest measurement conditions occurred during two general strikes that occurred from 13 to 15 June and from 20 to 21 July 1919. As the strike had been announced several days earlier, Majorana was able to prepare the experimental setup and to make all adjustments to take advantage of this occasion (Majorana, 1919-20b, p. 26).

The room where the experiment was performed was kept at a stable temperature (it would vary less than 2° C during daytime). A typical series of measurements would take a few hours. The enclosure around the test body guaranteed that its temperature could never vary more than a few hundredths of a degree during the experiments. The vacuum inside the apparatus was kept by a Gaede mercury pump that was turned on many hours before any observation was made, and that was kept running during the measurements. It maintained an internal pressure lower than 0.1 mm of mercury. Majorana computed the possible buoyancy effects and noticed that they were smaller than the sensitivity of the balance.

The test body had to be placed exactly at the centre of the hollow sphere, and the level of the mercury inside the wood cylinder had to be adjusted so that the hollow sphere was exactly between its upper and lower levels. The position of all solid parts of the apparatus was established with an accuracy of about 0.1 mm using a cathetometer. The motion of the liquid mercury was controlled at a distance, and its level was detected by electrical contacts. After several improvements of this system, Majorana was able to control this level with an accuracy of 0.1 or 0.2 mm.

The sensitivity of the balance was checked using the 1 mg rider, and it was noticed that the sensitivity was not constant. It was necessary first to prepare the experiment — to produce the vacuum and then to wait for several days until the system would become stable. After three days, the sensibility would remain nearly constant (varying about 1%). Majorana also checked the sensibility of the balance, filling the wood cylinder with mercury up to the level of the test body and observing the resultant Newtonian force of attraction. The computed force was 32.6 μ g, and the observed displacement of the light spot agreed with the predicted value of 5.6 mm.

The balance beam oscillated continuously with a period of about 2 minutes, and therefore the light spot was never at rest: it oscillated with an amplitude of about 1 mm. In addition, there was also a slow drift of the equilibrium position. All position measurements were therefore the result of three observations: the upper position h_1 of the light spot in one oscillation, its lower position h_2 in the same oscillation, and its upper position h_3 in the next oscillation. The mean position of the spot was computed as $p = (h_1 + h_3 + 2h_2)/4$. Each position was measured to 0.1 mm, but Majorana used two decimal places to represent the mean.

Observations were made in the following way. When the apparatus had attained stable conditions and the wood cylinder was full of mercury up to the required level, the position of the light spot on the scale was measured, to within 0.1 mm, by the method described above. This would take 2-3 minutes. Let the first mean position be C_1. Then, mercury was withdrawn from the hollow wood cylinder. This operation took about 2 minutes. Then the position of the light spot was measured again (S_2). Immediately afterwards, mercury was introduced again in the hollow wood cylinder, and its level was adjusted. This operation took about 3 minutes. Immediately after the adjustment of the mercury level the position of the light spot was determined again (C_3). If the posi-

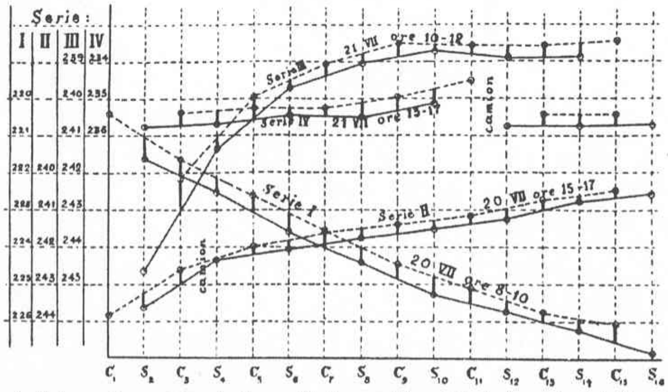


Fig. 7 – In Majorana's experiments the equilibrium position of the balance kept drifting all the time. To detect weight changes he made successive determinations of the equilibrium position when the test body was surrounded by mercury (C marks) and without mercury (S marks). In this graph, the points corresponding to measurements without the gravitational shield are joined by full lines, and the points corresponding to measurements with the gravitational shield are joined by dotted lines. In each series of measurements the two lines are clearly distinct and roughly parallel to each other.

tion of the light spot did not drift, C_1 would be equal to C_3. As a matter of fact they were always slightly different. For that reason, instead of comparing S_2 with C_1 or C_3, Majorana compared it with their mean $(C_1 + C_3)/2$. He was careful to make sure that the time intervals between the three measurements were equal. A graph presented by Majorana (Fig. 7) exhibits four series of measurements. One can perceive the slow drift of the equilibrium position, and it is easy to perceive that "C" measurements (those with mercury surrounding the test body) and "S" measurements (those without mercury) show a distinct difference.

Each series usually took a few hours, and during this time it was possible to obtain 10 to 30 measurements. In the strike days of 20-21 July 1919 Majorana was able to obtain 57 values of the weight change of the test body when mercury was introduced in the wood cylinder. In all cases he observed a weight *decrease*. The mean of these 57 observations was 0.358 ± 0.012 mm corresponding to a weight change of $2.09 \pm 0.07\ \mu$ g.

It was necessary to correct this result taking into account several known influences, however. In each experiment, about 100 kg of mercury were displaced from 6 containers to the wood cylinder and back to the containers. The test body was placed exactly at the middle of the containers and of the wood cylinder; therefore it experienced no resultant gravitational force. However, it was necessary to take into account the gravitational attraction of the mercury upon the balance beam and upon the counterweight. Majorana computed these effects and noticed that they were not negligible. When mercury was displaced to the wood cylinder, the Newtonian gravitational forces would simulate a

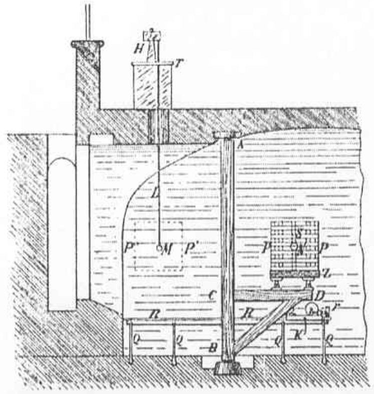
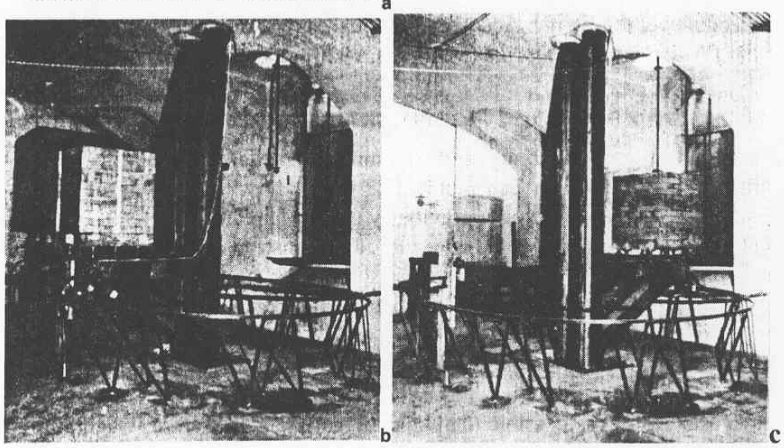


Fig. 8 – Majorana's second experimental setup (a) made use of a large lead cube *PP* as a gravitational shield. The test body *M* in the basement was attached to a balance *H* kept at the ground floor of the building. The two halves of the lead cube were supported by wood structures that could rotate around the pillar *AB* and be brought to the position *P'P'*. Measurements were made both with the test body surrounded by the lead cube and without it. The photographs show the actual arrangement, with the lead cube away from the test body (b) and enclosing it (c).



weight reduction corresponding to 1.12 μ g (that is, about half the observed effect). Therefore, discounting the attraction forces, the net measured effect was a weight decrease of 0.97 μ g.

Could this decrease be due to other classical causes? It was natural to check whether a small error in the position of the test body inside the hollow sphere, or a small error in the position of the mercury level, could explain this weight decrease. However, Majorana was able to show that it would be necessary to introduce a difference of about 5 mm of the upper level of mercury to account for the observed effect, and he was sure that the uncertainty of the mercury level was below 0.2 mm. An asymmetry of the wood cylinder or uncertainties in positioning the hollow sphere and the test body at the centre of the mercury shield could only produce weight changes of about ± 0.09 μ g, according to him.

Electrical forces were easily dismissed, because the whole apparatus was electrically shielded and connected to the earth. Magnetic forces, however, could be in play and Majorana made several tests to check this possibility. He finally dismissed this classical explanation, too. After taking into account all known influences and possible errors, he arrived at the final result: when the test body was surrounded by mercury, its weight underwent a change of $-0.97 \pm 0.16\ \mu$ g. Taking into account the size of the wood vessel and the density of mercury, Majorana computed the following value for the constant h:

$$h = (6.7 \pm 1.1) \times 10^{-12} cm^2 g^{-1}.$$

The value obtained in this measurement was compatible with the previously determined upper limit of 7.65×10^{-12} cm^2 g^{-1}.

Applying this result to the Sun, Majorana computed that its real density should be about three times its apparent density. This result was, however, computed from the simple model of a sphere with uniform density.

The above described results were also published, in summary form, in the proceedings of the French Academy of Sciences (Majorana, 1919a, 1919b) and in the *Philosophical Magazine* (Majorana, 1920).

6. Majorana's Second Measurement

Two years after the first series of measurements, Majorana repeated the experiment, but this time he surrounded the test body with 9,603 kg of lead instead of the 104 kg of mercury previously used (Majorana, 1921-22). For practical reasons, the mass of lead had a cubic form, instead of the cylindrical form used in the case of mercury. Instead of a solid block, he used 288 lead bricks to build two equal half-cubes that could be joined around the test body or moved away from it.

According to the previous measurement, and supposing that gravitational absorption depended only on density but not on other properties of the shielding substance, it was possible to anticipate that the reduction of weight, in this case, should be 5.4 times greater. Therefore, it was expected that the new measurement would afford an improved value of the gravitational absorption constant h.

In this second experiment, the absorption of gravity was produced by a lead cube with dimensions of 95 cm and total weight close to 10 tons—that is, about one hundred times the mass of mercury employed in the first experiment. The Newtonian attraction produced by the lead cube would be correspondingly larger, and to avoid strong perturbations upon the counterweight and the apparatus Majorana increased the distance between the test body and the balance (Fig. 8). The lead cube was mounted in the basement of the building. The balance (H) was on the ground floor, and a hole connected the two rooms. The two separate half-cubes could be moved 3 m away from the test body (M), by rotating them around the axis (AB) of their supports.

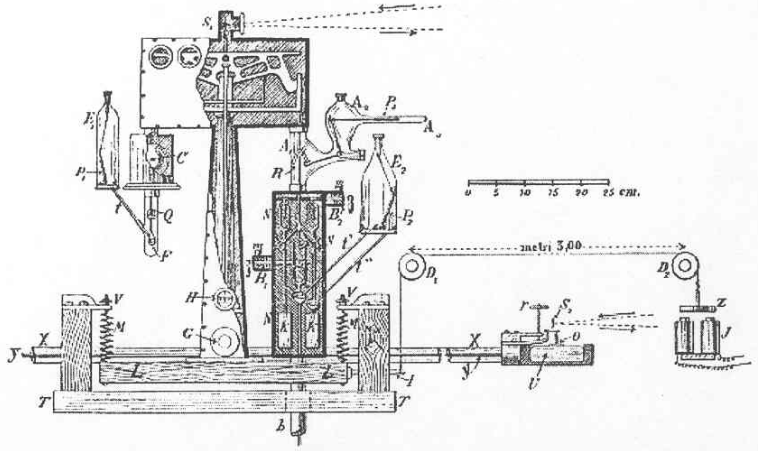


Fig. 9 – In the case of Majorana's second experimental setup, the displacement of the heavy lead blocks produced a noticeable tilting of the balance with a consequent change of the equilibrium position. To avoid this problem the Italian physicist built a special support for the balance that could be adjusted from a remote observation place, to cancel the tilting.

Majorana improved his apparatus to avoid several previous problems. There were, however, huge new experimental problems. The motion of the large mass of lead produced a small but relevant bending of the whole building where the experiment was made. The building deformation produced a tilting of about 10" of the balance. It was necessary to measure and to attempt to compensate for or evaluate all such changes. Majorana chose to compensate for the tilting, through a suitable mounting of the balance upon a platform that could be brought back to a horizontal position after motion of the lead shield (Fig. 9). He devised special ways of detecting a tilting smaller than 1" and he could compensate these changes using a small electromagnet.

It was necessary to take into account the attraction of the lead blocks upon the counterweight, as in the former experiment, but there were new perturbations. The lead blocks were held by massive wood pieces, and this suspension produced relevant forces both upon the counterweight and upon the test body. In addition, the lead blocks were moved by an electric motor and its Newtonian attraction had also to be taken into account. Majorana could not avoid using some iron pieces in the underground arrangement, and there were significant magnetic effects upon the balance.

The Newtonian effects were computed and taken into account in the calculations. The magnetic forces were measured by disconnecting the test body from the balance and using a third equivalent weight at the balance level instead.

In one typical measurement, Majorana observed a gross weight change equal to $+1.04\,\mu\text{g}$ (that is, a weight *increase*) when the test body was surrounded by the lead blocks. However, in this position the magnetic influences produced a downward force equivalent to +1.47 μ g and therefore there was a non-magnetic *upward* force of 0.43 μ g. The displacement of the lead blocks, together with its suspension and other attached bodies (electric motor, *etc.*), produced a downward Newtonian effect equivalent to 3.78 μ g, and the Newtonian attraction of the lead blocks upon the counterweight produced an upward effect equivalent to 2.75 μ g. Taking all these forces into account, there remained a net upward force of 1.79 μ g that was interpreted as a weight decrease produced by the absorption of gravitation.

Notice that the systematic errors were very large—larger, indeed, than the measured effect. In these circumstances one could wonder if Majorana could be measuring anything at all. Majorana himself was worried about this, and made a delicate test. He put a 15 kg lead disk at the floor of the basement room, below the test body. The Newtonian gravitational attraction produced by this lead disk upon the test body amounted to a few μ g. Repeating his experiment, he noticed that he could measure this effect—that is, the errors did not mask a very small influence such as this. Therefore, he concluded that the measured effect was real.

Majorana discussed other possible explanations of the observed reduction of weight. Perhaps the test body was not exactly at the centre of the lead shield, *etc.* However, a downward displacement of 5 mm was necessary to produce the observed weight reduction, and he was confident that positioning errors were smaller than 0.5 mm.

Taking into account all corrections Majorana obtained in 19 series of observations the mean reduction of weight of 2.01 ± 0.10 μ g (Majorana, 1921-22, p. 144). This was about half the expected value. Therefore, in the lead experiments, Majorana obtained a different value for the constant *h*:

$$h=(2.8\pm 0.1)\times 10^{-12}cm^2g^{-1}.$$

This difference could be ascribed either to experimental errors, or to a dependence of gravitational absorption on chemical composition of the absorbing body. Majorana did not, however, choose any of these alternatives. He did urge other scientists to reproduce his experiments in order to check his results.

7. Majorana's Later Work

Majorana's experimental work was never criticised. Indeed, when one reads the detailed account of his measurements, it is very difficult to suggest any source of error that he had not taken into account. Discussion following the publication of these results focused on its consequences and compatibility with other accepted results. Majorana himself always stressed the importance of reproducing his experiments in order to check his results, but no one else ever performed them. Albert Abraham Michelson once wrote to Majorana asking his permission to reproduce these experiments in the Mount Wilson Observatory. Majorana agreed enthusiastically, but the experiment was never reproduced. Perhaps Michelson gave up because he perceived that it was very difficult to reproduce or to improve that delicate experiment with available instruments.

In 1930, Majorana was invited to present a lecture to the French Physical Society. He talked about his gravitational experiments (Majorana, 1930). There, he again remarked:

> I really do not intend to state that my experiments (...) are completely conclusive. However, in my opinion, it would be useful if my experiments could be repeated by other more skilled colleagues that could make use of improved means. It could certainly occur that these eventual researches would conclude that the *effect* that I have found should be reduced in a greater or smaller extent, or that the limit of sensitivity or the observational errors do not really allow the certain determination of this effect. Even in this case, however, the physicist would do a work useful to scientific progress (Majorana, 1930, p. 314).

Majorana's experiments had been performed in the Physics Laboratory of the Turin Polytechnic. At the end of 1921, however, Majorana assumed the chair of Physics at the University of Bologna, as a successor to Augusto Righi. It seems that the new laboratory was better equipped than the former (*cf.* Perucca, 1954, p. 359). Majorana began a new series of experiments on absorption of gravity, but their detailed account was never published.

The main difficulty encountered by Majorana in his experiments had been the deformations of the building resulting from displacement of approximately 10 tons of lead. In order to avoid this problem, in Bologna Majorana reduced the weight of lead to only 380 kg. The arrangement of the balance was also different: a cylindrical lead shield was successively placed around each of *two* test bodies attached to the balance, in order to double the effect. Majorana stated that there were new sources of error and that it was impossible to derive any reliable value for the coefficient of absorption of gravitation from these measurements (Majorana, 1930, p. 321).

At Bologna, Majorana also tried to improve his mercury experiments. In this case, a new arrangement of the mercury vessels was chosen, so that its whole weight was always applied to the same point of the pavement. In 1930, Majorana was still improving the suspension of his balance and could present no quantitative results:

> The few measurements that have already been done seem to give results that confirm the sense of the formerly established effect, that is, an absorption of gravitational force. Although I cannot provide today quantitative results on the searched for effect, I am confident that with the new apparatus that is now under test I will be able, after some time, to say my definitive word *on the subject* (Majorana, 1930, p. 321).

Majorana's new measurements were never published. What happened? It seems that other interests had called his attention. Around 1930, Majorana was deeply involved in the development of communication by ultraviolet and infrared radiation, for military purposes (see Majorana 1941, pp. 81-82). It seems that his gravitational experiments were successively postponed and never finished. Indeed, in 1941 Majorana still referred to his Bologna attempts, remarking:

> The effect is of the same order of magnitude as that already observed in Turin. However it was impossible for me to establish its precise value in a definitive way. There are many causes of perturbation that act in an inconstant way when the experiment is varied. Notwithstanding this, hitherto the existence of the effect has always been confirmed. These are highly delicate researches that require months and years of accurate work for their preparation. If they are improved, they may in the future provide the last word on this interesting subject (Majorana, 1941, p. 80).

This future time never arrived. To the time of his death, in 1957, Majorana published several works that refer to his gravitational experiments*, but he was not able to repeat them.

8. Did Majorana Measure the Absorption of Gravitation?

In the 1920's everyone agreed that Majorana was a careful researcher, and his experimental method was never criticised. There are, however, three doubtful points.

First: in his measurements the attained sensibility was of the same order of magnitude as the measured effect. Indeed, any single position of the light spot on the scale was read within 0.1 mm, corresponding to a weight change of 0.6 μg. In the mercury experiments the net measured effect was a weight decrease of 0.97 μg, and in the lead experiments 2.0 μg. Many measurements were taken, and the mean exhibited a small standard deviation, but it is always risky to attempt to measure an effect of the same order of magnitude as the sensibility of the measuring apparatus.

Second: known systematic errors were of the same order of magnitude as (and sometimes larger than) the measured effect. Majorana was always attempting to reduce these perturbations, and in some cases it was easy to see how his experiments could be improved. For instance: the magnetic effects upon the balance and the Newtonian effects produced by the lead masses upon the counterweight could be reduced to about 25% if Majorana could transfer the balance to the next floor of the building. It seems that in the Bologna experiments he was trying to reduce several perturbations, but he could not achieve definitive results.

Third: Majorana did not make public all his experimental results, and he certainly *chose* some of his measurements for publication. The mercury results presented by him were computed using only the 57 measurements he obtained on the 20th and 21st July 1919. What about all other measurements he made? And why did he never publish any data of his Bologna experiments? It is likely that he would have published more data if they were consistent with his previous results. Maybe in different series of experiments he obtained widely different effects and saw that no conclusion could be drawn from the complete set of

* The last ones seem to be Majorana 1957a, 1957b.

data he had obtained. Only a careful study of his unpublished laboratory notes (if they have survived) could elucidate this point.

Perhaps the absorption of gravitation does not exist, and Majorana was measuring some unknown variable influence. Indeed, both in old gravitational experiments and in recent ones, it is usual to find unexplained systematic effects (Cook 1987, 1988). As Cook put it, "it is difficult to attain an adequate understanding of experiments at the limit of available techniques" (Cook 1987, p. 76). Majorana was certainly pushing the sensibility of weight measurements to its limit. Although he was a careful experimenter, some systematic error might be responsible for his results.

However, Majorana's measurements cannot be dismissed just because it is possible to *doubt* they are correct (and because they conflict with the most widely accepted gravitational theory). Until an improved reproduction of his experiments yields a null result, one should accept that *there is* observational evidence of the existence of gravitational absorption by matter.

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