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G. Gallinaro, M. Marinelli and G. Morpurgo: THE MAGNETIC LEVITATION ELECTROMETER, II - A PROGRESS REPORT.

SUMMARY -

This is a progress report of the second version of the magnetic levitation electrometer; this version makes use of the feedback levitation of ferromagnetic bodies, instead of the diamagnetic levitation of graphite, used in the construction of the first magnetic levitation electrometer$^{(1)}$. As illustrated in the introduction, the sensitivity is expected to be about 100 times larger than that of the previous instrument; moreover the variety of substances which can be explored is increased.

The project described here started in 1971; in spite of the fact that the completion of the instrument can still take some time, we are now reasonably confident (for the reasons to be explained in the text) that the requirements of the project can be fulfilled.

1. - INTRODUCTION. -

In a series of papers published in between 1965 and 1970$^{(1)}$ a new instrument was described, the magnetic levitation electrometer, which had been constructed to detect or exclude the presence of stable fractionally charged objects inside matter.

It was possible to study, by the use of the magnetic levitation electrometer a total amount of matter (pyrolitic graphite) of 3.4 x x 10^{-6} g. (corresponding to about 2 x 10^{18} nucleons) and to exclude the presence, inside that amount of matter, of stable quarks with charge ± 1/3 or ± 2/3 electron charges. The measurements were performed on irregular grains of pyrolitic graphite of different size; the maximum mass of the individual grain measured was 4 x x 10^{-7} g; because a measurement of charge on such big grains was possible with a precision $\sim 1/20$ e, the "sensitivity" of the instrument was $\sim 5 \times 10^{4}$ times that of a "typical" Millikan measurement; the "typical" oil droplet used by Millikan had in fact a mass around 10^{-11}g.

There is little doubt that a further increase in sensitivity by an order of magnitude would have been possible by the same instrument; however when, in the early 1971, we decided to improve as much as possible the "sensitivity" of our apparatus, it was felt interesting, in spite of the large effort which this would have implied, not only to increase the mass as much as possible, but also to change, at the same time, the type of substance subjected to analysis. The reasons were two:

1) it cannot be excluded that, also if the quarks exist, they are not abundant in the sample of pyrolitic graphite used;
2) if one has in mind (compare the ref. 1b) a process of enrichment using, say, an electrolysis of water, this process is easier if one has to do with a metallic grain.

This attempt to explore a substance different from graphite does not alter at all the basic idea of the experiment for which we refer to(1); it implies, however, a change in the levitation mechanism; one has to forget the very convenient mechanism based on the comparatively high diamagnetism of pyrolitic graphite at room temperature (which property made the construction of the first levitation electrometer so fast) and turn to one of two possibilities which have already received attention:

a) diamagnetic levitation of a superconductor(2);
b) feedback levitation of a ferromagnetic substance (a la Beams)(3).

At this point we argued that if we were going to lose the simplicity inherent in the (room temperature) levitation of graphite, we should be repaid by having a more open geometry, or, in other words, more space in all directions around the levitating object. This freedom can in fact make the control and the elimination of the spurious effects - discussed at length in ref. 1c - more easy; and can produce, in spite of our loss of simplicity in levitating, a final improvement of the whole instrument. This improvement could not be achieved with an instrument which levitates graphite because of the geometrical limitations imposed in that case by the necessity of having a high $\underset{\sim}{H}\,(\partial \underset{\sim}{H}/\partial z)$.

On examining under this perspective the two options a) and b) above, it seemed to us difficult to be able to reconcile the requirement of liquid helium temperature (necessary to ensure the levitation of a superconductor) with an easily accessible and open geometry.

We therefore decided to try the option b) - feedback levitation: and decided to examine if this option could be compatible with an open geometry and also allow a resonance experiment in vacuum.

The reason for an open geometry has been already explained: the movable platelets have been one of the important factors for the success of the experiment with graphite (elimination of the spurious effects); we are not willing to abandon this requirement; moreover an open geometry now allows to have wide plates so as to decrease, as much as possible, the gradients of the applied electric field.

The reason for a resonance experiment in vacuum is also obvious: because we are going to increase the mass of the objects with respect to the maximum value used in the previous graphite case - by a factor 10^2 as we shall see - we certainly cannot start with a reduction in the sensitivity of the technique. Such a reduction would certainly be there if we performed a non resonance (static) experiment.

At the same time, and even more important, a resonance experiment allows the use of the standard lock-in techniques which will be shown to be very effective in the present case.

Of course a prerequisite for a resonance experiment is vacuum; vacuum is important, at the same time, to avoid thermal drifts, spontaneous changes of charge and electric discharges. In conclusion: 1) a wide geometry, 2) vacuum, 3) a resonance experiment exploiting noise filtering techniques, are the three requirements on which the project to be described in the following sections will be based. The purpose of the rest of this report will be precisely that of describing the project and its present status; although the completion of the construction of the instrument can still take some time, we are now reasonably confident, as we shall see, that the three requirements stated above can be satisfied; and that a good magnetic levitation electrometer operating with steel balls of mass 3.3×10^{-5} g or higher can be constructed.

2. - SOME ORDERS OF MAGNITUDE -

Because the object to be levitated - a steel ball with a diameter of 2/10 of a millimetre-has a mass $M = 3.3 \times 10^{-5}$ g, which is almost 100 times that of the heaviest object used in the graphite experi ment(1), it is appropriate to examine briefly the orders of magnitude involved in the new version of the electrometer.

The magnetic valley which we are going to use will be characterized again by a frequency $\nu_o = \omega_o / 2\pi$ around 1 Hz; a much lower frequency could be easily achieved, but it would not allow a convenient exploitation of the lock-in techniques.

We recall the formula which gives the amplitude Δ of oscillation of our object at the top of the resonance:

$$\Delta = \frac{Q\, E_o}{\nu_o^2 M} \frac{N_{1/2}}{\pi^2 \ln 2} \qquad (1)$$

Here E_o is the amplitude of oscillation of the square wave impressed electric field, ν_o its frequency - which is assumed to coincide with the resonance frequency of the magnetic valley-Q the charge of the object; $N_{1/2}$ characterizes the damping, as described in ref. 1c ($N_{1/2}$ is the number of complete oscillations after which the oscillation amplitude, when no force is applied, reduces to 1/2 of its initial value).

Assuming $N_{1/2} = 50$, $Q = e = 1.6 \times 10^{-19}$ Coulomb, $\nu_o = 1$ Hz, $E_o = 2 \times 10^5$ volt/m we obtain from (1):

$$\Delta = 7.1\,\mu \qquad (2)$$

In the above conditions we therefore have for an object with unit charge an oscillation excursion of 14.2μ. To establish the presence of a charge 1/3 we need a sensitivity ten or twenty times better than this. The goal is therefore that of detecting an oscillation excursion of one micron. It is important to underline that the problem is, essentially, a problem of signal to noise ratio. It was nice to find that there is however no problem at all in this respect: as we shall see our photodetector of the horizontal oscillation produces, in the present experimental conditions, a signal of ~ 8 mV per micron; its total - purely electronic - noise is less than 1 mV. Filtering reduces it to unimportant levels. The largest source of noise is, we anticipate, the random vibrations due to the traffic. However these too are quite compatible with the feasibility of the experiment. Note finally that an additional requirement which must be strictly enforced is that of having a long term stability in the frequency of the magnetic valley.

The same problems, of course, were present in the previous experiment; however the increase by one hundred in the mass of the levitating object (compensated only in part by an increase of the electric field), and the different geometry due to the different levitation systems, makes at first sight these problems more acute now. This first impression is however false, as we shall see; the main factor which completely overcomes this apparent decrease in sensitivity, and in fact produces an overall increase, is the very large improvement in the photodetection of the oscillation of the object.

3. - GENERAL REMARKS ON THE FEEDBACK MAGNETIC LEVITATION SYSTEMS -

The general idea underlying a feedback magnetic levitation system is, after the pioneer work of J. Beams, well established. The system consists of a coil producing a magnetic field acting on the ferromagnetic object to be levitated, of a light source and of a photodetector. The object is illuminated by a stable light source and its vertical position measured by a convenient photodetector; the amplified signal coming from the photodetector governs the current flowing in the coil, so as to create an equilibrium position for the object at some predetermined height z_o. The equilibrium with respect to displacements in the horizontal (x, y) plane can be easily achieved choosing properly the configuration of the magnetic field, which is essentially determined by the geometry of the coils and of theirs ferromagnetic cores. The Figure 1 below gives a general scheme of the situation.

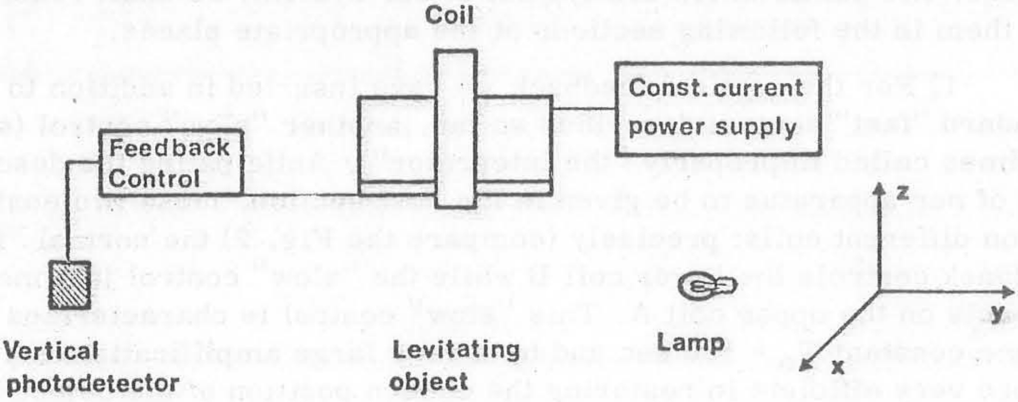

FIG. 1 - An illustration of the principle of feedback magnetic levitation.

To understand better the working conditions of a magnetic levitation feedback system we consider very briefly the vertical equation of motion of the levitating object for displacements z(t) in the vicinity of the equilibrium position. It can be shown that after the working conditions have been reached by a correct design and tuning of the feedback circuit, the vertical displacement z(t) satisfies a damped oscillator equation of motion:

$$M\ddot{z}(t) + \chi\dot{z}(t) + kz(t) = F_z(t) \tag{3}$$

Here $F_z(t)$ is the z component of any force, either random (noise) or due to systematic drifts, tending to displace the object.

An assumption underlies the simple equation (3): that the parameter k/M in the equation (3) must be smaller than some value ω^2_{max}; this value is determined by the induced Foucault currents and, if these were hypothetically absent, by the band pass of the electronic circuits. One of the problems in constructing a good feedback system is precisely that of reaching a value of ω_{max} as high as possible. Once this is achieved the equation (3) with constant (that is ω independent) values of χ and k provides a useful description of the motion of the object. The two parameters χ and k are expressible in terms of the various elements of the circuit; the selection of the values of these elements has to be performed$^{(4)}$ with the intent of optimizing the above parameters in the following sense: it must give rise to a restoring force - proportional to the coefficient k in (3) - as large as possible compatibly with a strong damping, given by the coefficient χ.

Although this section has been devoted to the general features of the feedback magnetic levitation systems, we anticipate here, nevertheless, two points which are typical of our system; we shall reconsider them in the following sections at the appropriate places.

1) For the vertical feedback we have inserted in addition to the standard "fast" control described so far, another "slow" control (sometimes called improperly "the integrator"). Anticipating the description of our apparatus to be given in the next section, these two controls act on different coils: precisely (compare the Fig. 2) the normal "fast" feedback controls the lower coil B while the "slow" control just mentioned acts on the upper coil A. This "slow" control is characterized by a time constant T_o = 100 sec and by a very large amplification; it is therefore very efficient in restoring the chosen position of the object if (and only if) the object is acted by disturbances which are comparatively slow, such as thermal drifts in the vertical magnetic force etc.; indeed this "integrator" was initially planned precisely with the purpose of compensating certain thermal drifts which were present when the feedback control on the lower coil B (compare the Fig. 2) was governed by a class A amplifier and, therefore, the average current in that coil was considerable, thus producing undesirable slow thermal drifts. Because we now work with a class B feedback amplifier in the B coil, this type of problems has disappeared; still we have kept the integrator which proves to be useful in making easier - and, in fact, almost authomatic - the procedure of starting the levitation of an object.

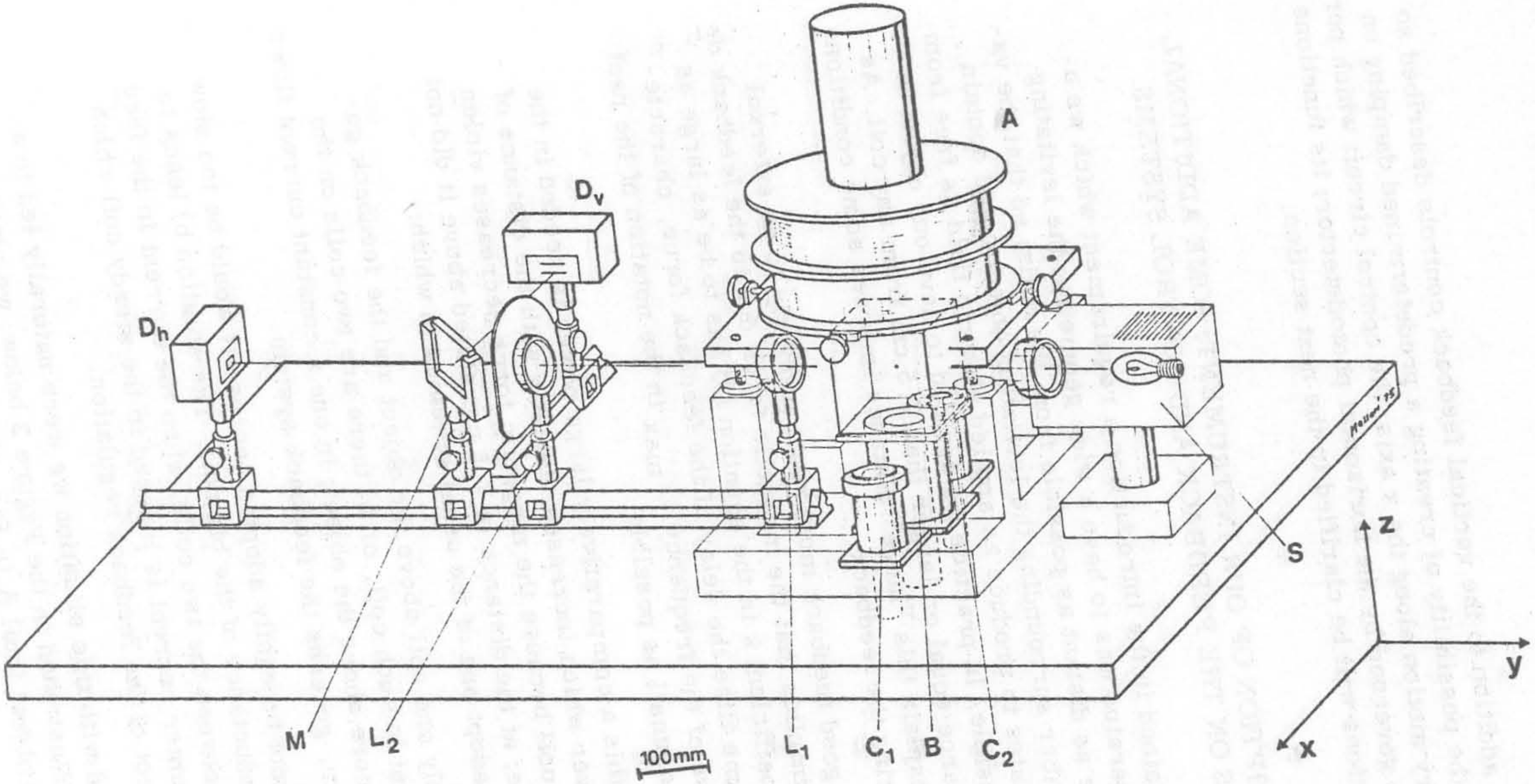

FIG. 2 - A schematic view of our instrument (all the details have been omitted and the scale has only an indicative character).

2) In addition to the vertical feedback controls described so far we have the possibility of creating a predetermined damping on the oscillatory motion along the x axis; the control circuit which performs this is governed by the horizontal photodetector; its functions and specifications will be clarified in the next section.

4. - A DESCRIPTION OF OUR INSTRUMENT; SOME ADDITIONAL REMARKS ON THE FEEDBACK AND CONTROL SYSTEMS.

As explained in the introduction a requirement which we asked to our apparatus was to have a wide geometry; the levitating object should be as distant as possible from the coils; so that the vacuum tight chamber surrounding the levitating object could contain wide movable plates to produce an applied electric field as free from gradients as possible. In practice we decided to have our object levitating at a distance equal or larger than 7.5 cm from any coil. As we are going to explain this "large" distance imposes some conditions on the coils creating the feedback.

Clearly a good feedback must react promptly to an external disturbance; this implies that the magnetic force due to the feedback determined by the coefficient k in the equation (3) has to be as large as possible; at the same time the delay of the feedback force, characterized by the inverse of the frequency ω_{max} in the notation of the past Section, must be as small as possible.

To achieve this a comparatively large power is needed in the feedback coil; a power which increases violently with the distance of the object from the coil because the magnetic force decreases violently with this distance; at the distance of 7.5 cm stated above it did not prove convenient to adopt one of the usual schemes in which:

a) there is only one coil above the object and the feedback governs the total current in such coil, or b) there are two coils on the same ferromagnetic core above the object; in one a constant current flows and the other, smaller, governs the feedback system.

Solution a) cannot be easily adopted because it would be too slow due to the large self inductance of the big coil. The solution b) leads to a transformer effect between the two coils: when the current in the feedback coil changes a counter current is induced in the steady coil which largely cancels the effect of the feedback regulation.

Being confronted with this situation we were naturally led to a third solution which is illustrated in the Figure 2 below: we placed a coil above the levitating object (coil A in Fig. 2) to create a steady strong magnetic field; another coil (B) was placed below the levitating object; this carries the feedback control current. The total magnetic field $\mathbf{H}$ is the sum of the magnetic fields due to A and B: $\mathbf{H} = \mathbf{H}_A + \mathbf{H}_B$. Because the magnetic force acting on the object is quadratic in H (its z component is proportional to $\mathbf{H}\,(\partial \mathbf{H}/\partial z)$), the z component of the total magnetic force acting on the object is:

$$f_z = \eta \left(\mathbf{H}_A \cdot \frac{\partial \mathbf{H}_A}{\partial z} + \mathbf{H}_B \cdot \frac{\partial \mathbf{H}_A}{\partial z} + \mathbf{H}_A \cdot \frac{\partial \mathbf{H}_B}{\partial z} + \mathbf{H}_B \cdot \frac{\partial \mathbf{H}_B}{\partial z} \right) \tag{4}$$

where η is, for a given object, a constant.

We also found convenient to work with the feedback B coil at an average value zero of the current i_B - that is to use a class B amplifier in the feedback circuit. It follows that, to first order in i_B, the component f_z of the force does not contain the last term in (4); and that the force which the feedback coil produces - represented by the second and third term in (4) - has a zero time average for random external disturbances.

The solution described above proves to be very satisfactory. There is no unwanted interaction between the "steady" large coil A and the feedback coil B because their cores are separated by a distance of 15 cm. There is no heating of the coil B because it works at zero average current. The stability with respect to displacements in the horizontal plane is authomatically produced by the configuration of the magnetic field. Finally on shaping appropriately the lower part of the upper iron core and positioning conveniently the ferrite core inside the feedback coil B, a frequency of oscillation of the object along the x direction (compare the Fig. 2) of 1 Hz is obtained, as requested.

Note that the core of the feedback coil B is in ferrite to minimize the delay of the feedback system due to the Foucault currents; the core of A is in normal iron; one of the advantages of this solution is that there is no problem in having around A large amounts of metallic materials, which is of course important for fulfilling easily the rather strict requirements of mechanical stability and precision.

The upper iron core is shaped so as to guarantee a considerably higher frequency of free oscillation along the y axis (≈ 2 Hz) than along the x axis, a point which is of some importance to avoid transfers of energy from the x to the y oscillations.

An additional characteristics of the system is the presence of the two smaller coils C_1, C_2 (compare the Fig. 2) which have a twofold purpose:

1) by raising or lowering their iron cores we can change the shape of the magnetic field and in particular change, if we wish to, the frequency of oscillation in the x direction. Of course all the measurements are going to be performed at a fixed height of these cores (so as to have a frequency of about 1 Hz, as already stated) but it was felt useful to dispose of this additional flexibility.

2) The coils C_1 and C_2 have also the essential purpose of creating an electronic damping of the motion of the object along the x axis. This can be done by governing C_1 and C_2 by a control circuit, responding to the x component of the velocity of the object; this quantity can be obtained, by derivation, from the signal given by the horizontal photodetector D_h; in this way the coils C_1 and C_2 can create on the object a damping force proportional to x. As we have stated this is now essential because the residual air pressure is totally unable to produce a sufficient "natural" damping; the reason is that the mass of the levitating object is much larger than that occurring in the graphite experiment. This possibility of creating an artificial damping is also very convenient because it allows to predetermine and to change, if necessary, the damping ($N_{1/2}$ in the eq. (1)) in the way which is more appropriate (an example of determination of $N_{1/2}$ is given in the Fig. 4). For instance in the preparation of the apparatus there are stages in which a small

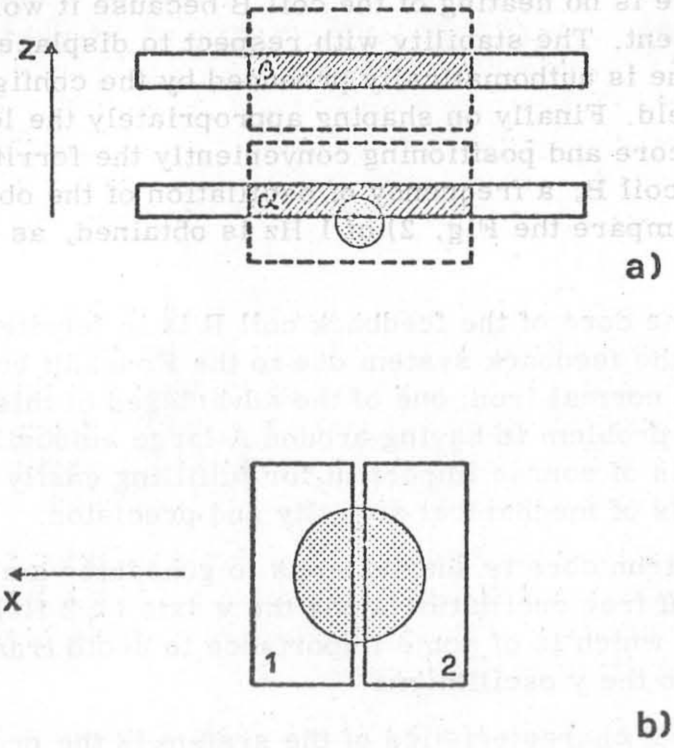

FIG. 3 - A few details of the vertical and horizontal photodetectors.

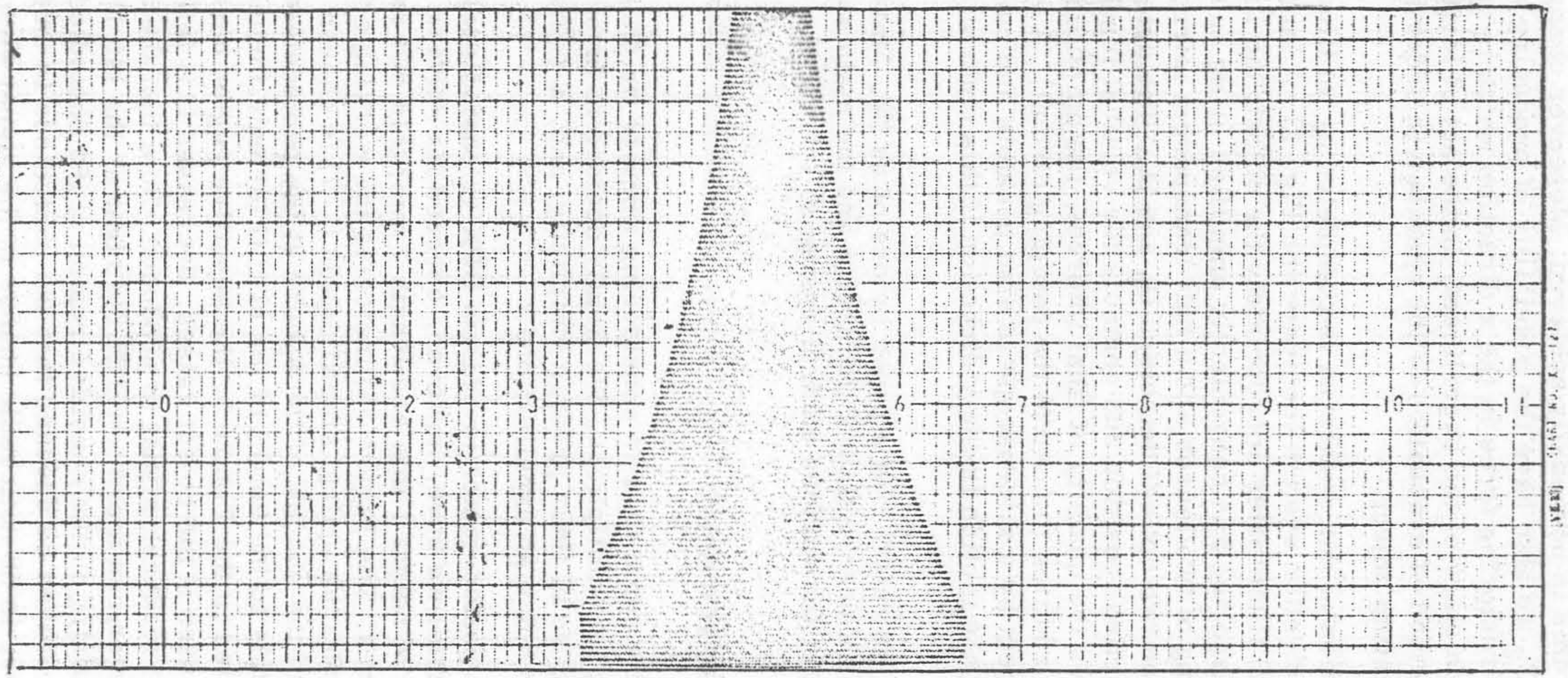

FIG. 4 - An example to illustrate the determination of $N_{1/2}$ (the signal is switched off and the number of full oscillations after which the amplitude reduces to one half is counted).

$N_{1/2}$ is convenient; this is now easily achieved. Moreover changing the control on C_1, C_2 we also have the possibility of producing a stronger horizontal restoring force in the x direction which is useful in the preparation stage of the experiment, in the act of levitation or during the period of evacuation of the chamber in order to avoid losing the levitating object.

The description of our apparatus is completed by an illustration of the optical detection system (compare the Fig. 2). A lamp L (at present of 100 W) illuminates appropriately the object; the image of the object is transported and conveniently amplified using an optical system consisting of two lenses and a half transparent mirror; it is thus reproduced on two optical detectors D_h and D_v. The detector D_v measures the vertical position and controls the vertical feedback system; D_h measures the quantity of final interest, the amplitude of the x oscillation (in addition to control the damping circuit). A visual inspection of the object by a microscope is also possible and can be used for controlling the motion in the y direction if this control is necessary.

To conclude we refer$^{(4)}$ to a paper by one of us (M. Marinelli, in preparation) for a description of the design and the main operating characteristics of the various control systems.

5. - THE PHOTODETECTORS -

We spent quite some time in considering whether we should use photodiodes or photomultipliers. We finally decided in favour of the photodiodes because of their greater simplicity; and, a posteriori, we consider this choice an excellent one.

The vertical photodetector (a Philips BPX 42 photodiode) has a size of 3.7 x 6.7 mm; we have, however, covered its surface except for a horizontal slit of height 1 mm and length 7 mm; this slit remains the only sensitive area. The Figure 3a) indicates the working conditions of the photodiode; the optical amplification ($\sim$ 7) is chosen so as to have a diameter of the shadow of the sphere at the photodetector of $\sim$1.5 mm, comparable to the height of the slit; if the equilibrium position is that indicated in the Figure 3, the sensitive region covered by the shadow increases if the object raises, decreases if it falls. In this way the vertical feedback signal is produced. Note that the object, if initially in the center, can move towards the right or the left by 3 diameters always remaining in the sensitive region of the photodiode and therefore levitating. It can be checked that the photodiode is uniform in the sense that there is no noticeable change in the signal when the shadow moves towards the left or the right without changing its height. This is of interest because no vertical movement is induced for this reason by the feedback when the object moves in the horizontal plane.

Another point of interest is the presence of a comparison photodiode (β in the Fig. 3a)) placed some millimiters above the photodiode (α in the figure) of which we have just described the operation. The photodiode α is coupled to β so that the total output is the difference of their signals. This differential photodetector has the advantage that if a variation of the overall intensity in the light occurs (the voltage applied to the lamp is well stabilized, but a priori the intensity of illumination might still drift or fluctuate) this does not affect the feedback system. The system reacts as it must to a vertical shift of the shadow on the photodiode α, but does not feel a variation of the intensity from the lamp L, even if comparatively strong.

The detector of the horizontal displacements (shown in the Figure 3b)) is based on a similar principle. The figure reproduces (more or less in scale) the situation of the two photodiodes - again two Philips BP X 42 - and of the shadow of the levitating ball when it is in its equilibrium position. The optical amplification on this detector is larger than that on the vertical detector. When the shadow moves, say, to the right, the signal from 1 increases, while that from 2 decreases (here 1 and 2 are the left and right photodiodes). Because the difference is taken, the two signals effectively add, so that the sensitivity is increased with respect to the case of just one photodiode; and again the differential method - appropriately calibrated - eliminates possible overall variations in the intensity of illumination, as for the case of the vertical detector.

We have been impressed by the sensitivity of this detector: we have already mentioned a value of 8 mV per micron of horizontal displacement of the object from its equilibrium position in our typical conditions of illumination, to be compared with an overall electronic noise less than 1 mV. If the motion in which we are interested is a stable periodic one - so that we are effectively disturbed only by the noise in a narrow interval of frequencies - it is clear that an amplitude of oscillation of a few Å is measurable in this way. The much higher precision which we now have - with respect to the graphite experiment - in measuring and recording the amplitude of the horizontal oscillation, is the main reason why the present version of the experiment is feasible. Note again, as already stated, that the major source of noise in our present situation is not the electronic noise quoted above, but the random vibrations due e.g. to the traffic. Finally two remarks are appropriate:

1) the above value of 8 mV per micron depends somewhat on the position of the lamp; it is only an order of magnitude; to be precise a calibration has to be redone each time some change is introduced in the position; values from 5 to 10 mV per micron have occurred depending on these positions.

2) The noise figure of less than 1 mV of the photodetectors stated above refers to some selected diodes; differences in the noise by at least a factor of ten were found between different photodiodes in the first sample we had.

6. - A FEW REMARKS ON THE PROCEDURE FOR LEVITATION AND ALIGNMENT. -

When the apparatus is aligned there is no difficulty in the procedure of levitation. It takes a few minutes. The sphere is placed on a small cylindrical support of graphite, which can be moved micrometrically; using this movement the upper edge of the shadow of the sphere is brought near to the center of the lower photodiode of the vertical detector, about one millimeter below the lower edge of the slit. The differential photodetector is adjusted, using a potentiometer, so that, in these conditions a small current flows in the feedback coil B; its magnitude is chosen so that, when the object is in the correct levitation position, this average current becomes zero. The current in the upper coil A is then raised slowly so as to reach a value for which the magnetic force on the object counteracts the gravity. At this stage the object, either spontaneously or by a very slight vibration impressed to the support, jumps to its feedback equilibrium position. As stated above the current in the feedback coil is now practically zero; a fine regulation can be performed, if appropriate, on the current of the main coil so as to bring the shadow exactly at the required height. Finally the support of the object is removed and the vacuum tight box is closed.

Note that a support of graphite proved to be most appropriate for a proper execution of this stage; any other support, metallic or glassy, no matter how clean, has a much larger adhesion to the small sphere (there is no such problem for bigger spheres, say 1 mm. or more in diameter); so that, to detach the sphere, one had to produce strong vibrations with the result that often the sphere could not be stopped by the feedback system.

The description given above refers to the procedure of levitation once the apparatus has been aligned; as a matter of fact this procedure, once the correct levitation conditions have been selected, can be further simplified by the use of the "slow" control circuit of the upper coil (the integrator); this performs automatically, rather than manually, the part of the above operation which consists in increasing slowly the magnetic field of the upper coil. In other words, once the object is properly set on its support, the rest of the procedure of levitation is accomplished automatically.

The process of alignment, which is preliminary to the levitation procedure just described, implies a little more work; this work has to be performed, however, only once (except of course if one needs to remove one of the coils or to re-position their cores to introduce some modification in the instrument).

The basic reason why the procedure of alignment to be described has to be performed carefully is that the optical axis of the instrument and the magnetic axis must intersect to a precision of the order 1/10 mm or better if objects having a radius of that order of magnitude have to be levitated.

Indeed the equilibrium position of the object is along the magnetic axis of the instrument (assuming that this axis is vertical as it must be). The shadow of the object on the vertical photodetector must of course fall entirely in the sensitive region; in fact it should be at the center of that region so that the object can oscillate on both sides, along the x axis, as much as possible, without falling. This leads to the requirement of intersection stated above.

In practice, to achieve the alignment, one first aligns correctly the optical system by the help of a laser. The procedure for this is obvious; once this is done we know that if the object is prescribed to levitate in a point below the coil A along the laser beam, it will produce its shadow in the correct position of the vertical detector. The next step consists in putting a sphere of a millimiter radius on a wide and smooth horizontal graphite plane at the correct height; giving current to the upper coil so as to counteract almost completely, but not entirely, the gravity, this sphere moves to that position on the graphite plane from which it would jump up when levitating. If this position is well centered along the laser beam we are already in a good situation; if not the screws on the platform which sustains the coil A are used to displace horizontally the coil and its core until the desired position is reached. By repeating this procedure another time with a sphere of smaller diameter we arrive to what we may call a situation of zero order alignment. In this situation the object levitates and is also well centered, but it may show a sort of lateral instability (different from the feedback vertical instability which sets in if the parameters of the feedback circuit are not properly arranged, in particular if the feedback amplification is excessive). After some thinking we understood the origin of this instability. Suppose that, for instance, the magnetic axis of the lower coil is not on the same line as the magnetic axis of the upper coil: one possibility is that it is parallel to it but somewhat displaced; another that the two axes have some inclination. Then if no external disturbance is present so that no current flows in the coil B, the object remains stationary; but as soon as some current flows in B to correct for an external disturbance, the magnetic field which this current produces gives rise also to a lateral force on the object precisely because of the asymmetry just described. When the external disturbance stops or changes sign, the object goes back to or on the reverse side of its starting point so that a sort of oscillation starts.

To avoid this effect is not difficult; one can amplify artificially the above oscillation - sending a large oscillatory current in the upper coil - and produce the appropriate small displacements of that coil acting on the lateral screws. One can thus eliminate the effect entirely; in this way the procedure of alignment is completed.

7. - THE PRESENT STATUS OF THE EXPERIMENT; THE DIRECT DETECTION OF THE SIGNAL. -

We are now in a position to describe the present status of the construction of the instrument and the preliminary measurements which appear to justify the confidence expressed at the end of the introduction.

What we have done so far has been to insert in between the lower and upper coils a transparent (plexiglass) vacuum tight chamber connected to a diffusion pump. The small sphere (2/10 mm diameter) has been levitated, the plexiglass box closed and evacuated so as to reproduce, as far as the vacuum is concerned, the situation in the real metallic box which is at present under construction. In the plexiglass chamber there are no plates to produce the electric field; nor we have yet put in operation the system for charging and discharging the sphere (analogous to that of the graphite experiment). Therefore to examine the sensitivity of the apparatus when the sphere levitates inside the plexiglass box we cannot yet apply to the sphere an electric signal. We can however - and this is what we did - simulate the electric force by a magnetic force. This magnetic force is created by adding on the coils C_1, C_2 an auxiliary winding of a few turns and feeding it with a small current i'. We can thus create on the object a force displacing it along the x axis; and if i' oscillates at the proper frequency of the sphere in the magnetic valley along the x axis (~ 1 Hz), we can produce the desired resonance amplification in the amplitude of oscillation of the object.

In this way, by a proper choice of the magnitude of the oscillating current, we produce the same force on the sphere which would be produced if the sphere had unit charge and were acted by an oscillating electric field as in the real experiment. Obviously we cannot in this way explore the "spurious effects" extensively described in ref. 1c; we can, however, examine the signal obtained from the horizontal photodetector when the sphere oscillates under the action of the above magnetic force and see if the signal to noise ratio is acceptable; also, and this is equally important, we are able to check the long term stability of the instrument and, in particular, the stability of the magnetic valley, that is of the proper frequency. By choosing appropriately the magnitude of the oscillating current i' let us first produce an oscillation of the object which, after having set $N_{1/2} = 50$ and working at the resonance, has the amplitude given by (2), that is $7.1\,\mu$. This means that we have produced the same motion, at resonance, of a sphere of charge one, with $N_{1/2} = 50$ and an electric field of amplitude 2×10^5 V/m. It is first convenient to look directly in the oscilloscope to the signal from the horizontal photodetector, without using the lock-in.

According to the situation described above we thus adjust the current i' in the auxiliary coil until the oscilloscope shows a signal (peak to peak) of 2 x 7.1 x 8 mV = 110 mV; here we have inserted the value 8 mV per μ of the sensitivity of the horizontal detector mentioned several times.

The question of interest is now: which is the noise affecting this signal? We have already stated that the pure electronic noise from the photodetector (which we indicated to be globally less than 1 mV) is small with respect to the total noise which affects the oscillation of the object; also we stated that the main origin of the noise is, presumably, to be found in the mechanical vibrations due e.g. to the traffic. To avoid any confusion we repeat that in fact, at the moment, as we are going to see, the electronic noise from the photodetector is entirely negligible with respect to the other sources of noise. Indeed the observation of the oscilloscope in the conditions described above shows (compare e.g. Figure 5) that the amplitude of 110 mV. (peak to peak) changes randomly by an amount of the order 9% during the noisy hours of the day(and by a smaller amount during the night); stated differently the pure noise signal is around 10 mV during the day and usually much less during the night. This is a large noise; still, as these numbers show, we are already in conditions to detect well one electron charge and tolerably, although not satisfactorily 1/3 e, without any further processing of the signal. This answers the question asked above.

To proceed, that is to improve the signal to noise ratio, we have several possibilities among which we consider here only two:

1) to decrease the noise; if its main origin is in the vibrations of the basement this is possible in an obvious way, namely moving to a more quiet place. Our department is in a rather noisy district of the town, and our laboratory is, from this point of view, in a bad location inside the department.

2) Although the oscillating object itself is an extremely good mechanical filter and, therefore, if the noise is mechanical, the signal to

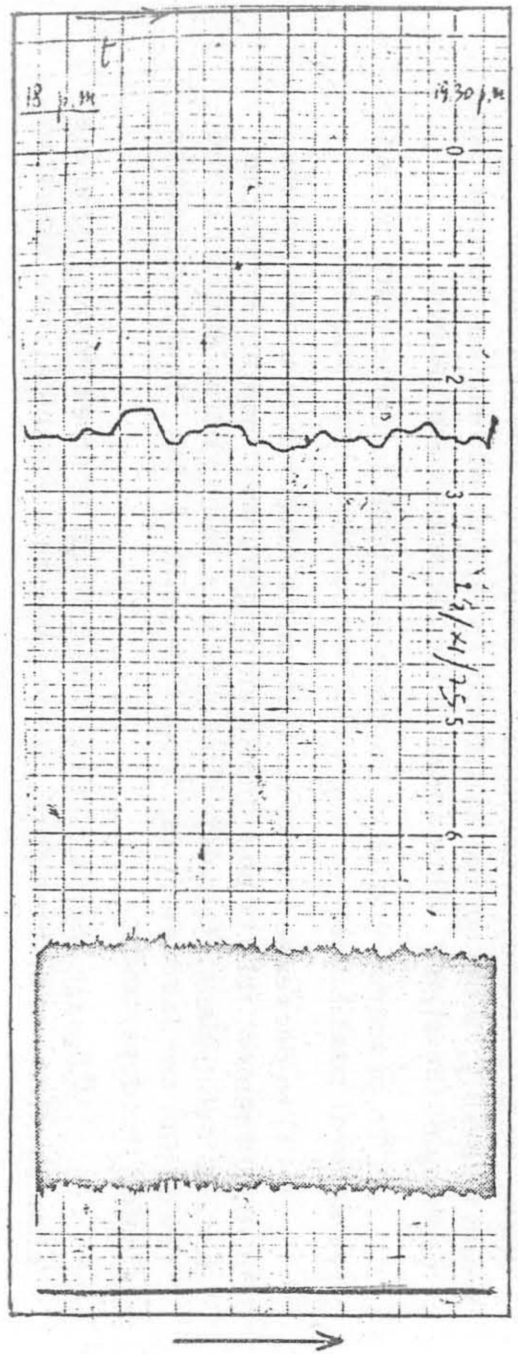

FIG. 5 - a) lower part (full band).
A plot of the oscillation of the object during one hour and half (from 18 p.m. to 19.30 p.m.) obtained recording directly the signal from the horizontal photodetector. The fact that a band appears and not a curve - as for instance in the figure 4 - is due to the slow movement of the paper in the plotter (6 cm/hour) as compared to the fast movement (5 cm/minute) used in obtaining the plot of figure 4. The sensitivity of the plotter for the pen producing the band is 500 mV/100 small divisions. The band has a width of 20 to 22 small divisions corresponding to 100-110 mV.
b) upper curve.
A plot of $V_{lock\text{-}in}$ from the same signal just described, as obtained from the second pen of the plotter; the sensitivity of this pen is 50 mV/100 small divisions and the zero level (absence of signal) is the heavy horizontal line near to the bottom of the plot; the signal, centered around 75 small divisions, corresponds thus to 37.5 mV; τ_L has been chosen to be 100 sec, $N_{1/2} = 50$.

noise ratio increases as $\sqrt{N_{1/2}}$, we can more conveniently and independently of the origin of the noise filter the signal by a lock-in, without increasing $N_{1/2}$ excessively.

Both these procedures 1) and 2) should be applied; clearly one should should start with 1) until easily feasible and next go on with 2).

However, because 1) takes some effort, we first started with 2). We sent the signal coming out from the horizontal photodetector to a lock-in amplifier, locked to the frequency of the oscillator producing the current i' (this oscillator was piloted by the same stable oscillator which had been used in the graphite case to produce the square wave electric signal).

In the next section we shall illustrate some typical results obtained by the use of the lock-in.

8. - SOME REMARKS ON THE USE OF THE LOCK-IN. -

To clarify the proper use of the lock-in in our situation the following remarks are first appropriate:

1) Call τ_{L} the integration time of the lock-in: for a given the lock-in acts (at 12 db/oct) as a filter of half-decay time $T_{(1/2)L}$

$$T_{\frac{1}{2}L} \simeq 1.5\,\tau_{L}$$

automatically centered, when locked, at the resonance frequency (to be more precise the above statement is correct if the harmonics of the resonance frequency are excluded; we come back to this in a moment). In our instrument we thus have two filters in cascade.: one is the oscillating object itself, which behaves as a mechanical filter characterized by a half decay time:

$$T_{\frac{1}{2}m} = N_{1/2}\,\frac{1}{\nu_r}$$

and the second is the sinchronous filter of the lock-in characterized by τ_{L} as we have just said. On increasing τ_{L} so that

$$T_{\frac{1}{2}L} \gg T_{\frac{1}{2}m}$$

we increase the signal to noise ratio with respect to that in the absence of the lock-in. This is the proper way of using the lock-in in our case. A compromise of course has to be found between the requirement of increasing the signal to noise ratio and that of dealing with acceptable waiting times. Only some practice in the ionization procedure and in the time needed to appreciate that the object has changed its charge will allow to decide the best values of $N_{1/2}$ and τ_L.

2) We mentioned previously that the harmonics of our signal should be eliminated if present; this is obtained by using the lock-in in the band pass mode rather than in the flat mode. A Q-value of 10 of the band pass filter has been used in all the records given below; the frequency width corresponding to such a Q value is much larger, as it must, than the width of the mechanical or lock-in filter.

We can now present a few typical results of the signal at the exit of the lock-in; this is done in the upper parts of the Figures 5 and 6 as well as in the Figures 7 and 8. The absolute value of the lock in signal $V_{\text{lock-in}}$ is related to the peak to peak $V_{\text{peak-peak}}$ amplitude at the entrance of the lock-in by:

$$V_{\text{lock-in}} = \frac{1}{2.82} V_{\text{peak-peak}}$$

The lock-in signal corresponding to a simulated one electron charge, that is to a peak-to peak amplitude of 110 mV (see above), must therefore be, approximately, 39 mV. This is in fact so as the Figures 5, 6, 7, 8 indicate (in fact it is slightly less because the entrance signal was slightly less than 110 mV). The point of interest is the level of noise on this signal. On comparing the Figure 6 with the Figure 5 it appears that there is a definite improvement in the signal to noise ratio at the exit of the lock-in passing from $\tau_L = 30$ sec (Fig. 6) to $\tau_L = 100$ sec (Fig. 5), the $N_{1/2}$ being the same (50) in both cases. Note that, as it appears from the plots of the peak-to peak amplitudes at the entrance of the lock-in, the entrance noise in the two cases is approximately the same (at least comparing the Fig. 5 with the right half of the Fig. 6, lower plots).

The Figures 7 and 8 are plots of the lock-in signal with $N_{1/2} = 50$ and $\tau_L = 100$ sec. The Fig. 7 refers to a period of ~ 8 hours during the day and the Figure 8 to an equally long period during the night. The noise in the graph of Fig. 8 appears to be very small (we have a signal around 37.5 mV with a noise much less than $\pm$ 1 mV (however during other nights the noise was somewhat larger). During the day (Fig. 7) we have a noise of $\pm$ 1.5 mV. In both cases we have an excellent stability (the fact that it is slightly worse in Fig. 8 than in Fig. 7 is due to circumstance that the thermal equilibrium of the upper coil had not yet

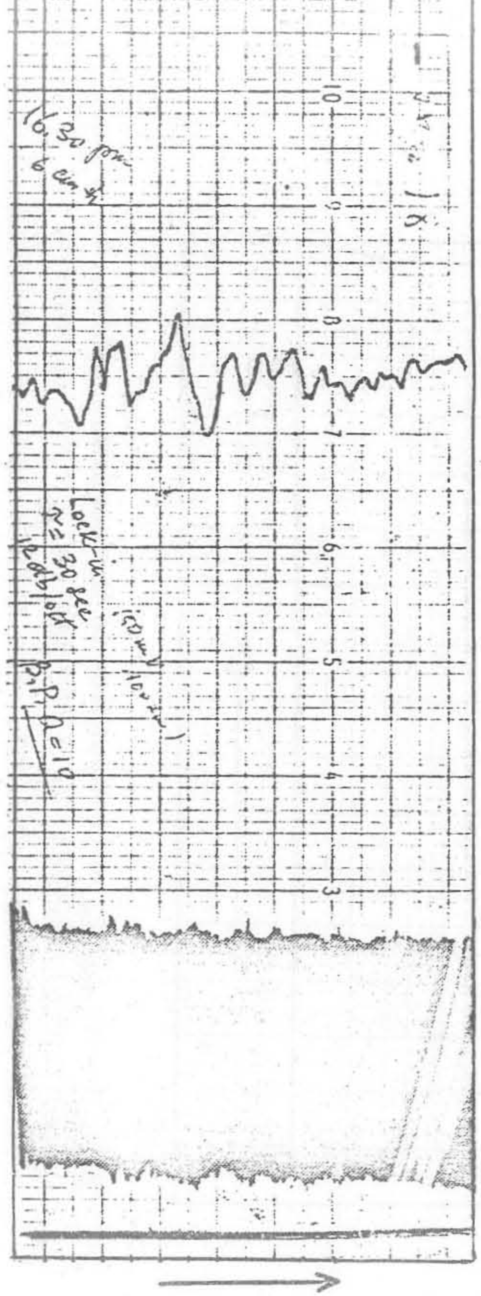

FIG. 6 - a) lower part (full band):
the same as for the lower part of fig. 5 during an interval of one hour and a half from 16. 30 p. m. to 18 p. m.

b) upper curve.
The corresponding $V_{lock-in}$ as illustrated for the figure 5, but with τ_L = 30 sec.

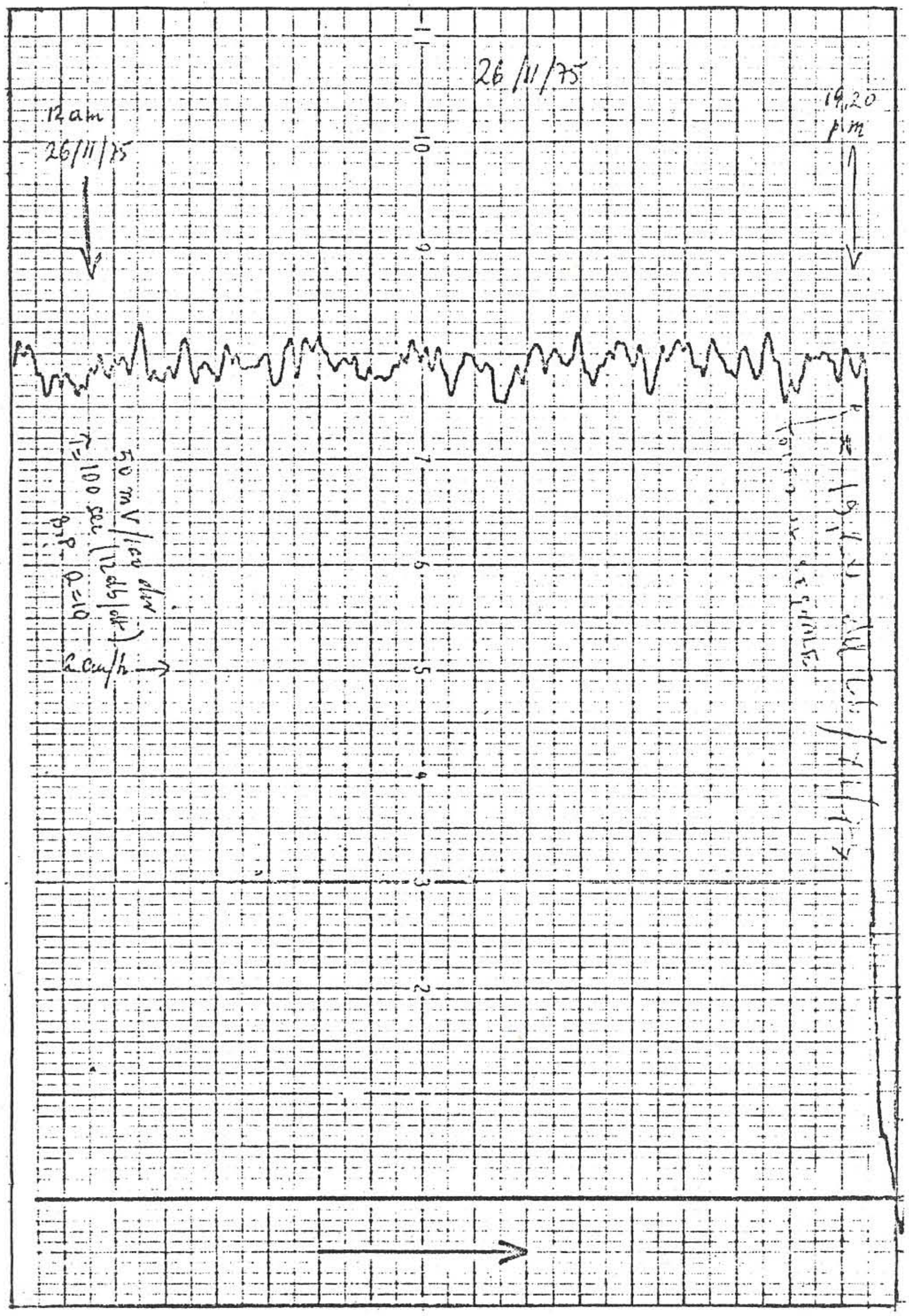

FIG. 7 - $V_{\text{lock-in}}$ corresponding to the conditions of fig. 5 (upper curve), namely τ_L = 100 sec, $N_{1/2}$ = 50, sensitivity = = 50 mV/100 small divisions. The zero is again at the heavy horizontal line at the bottom, as it appears also on observing the fall of the signal when, near to the end, the excitation is switched off. The velocity of the paper is now 2 cm/hour and the graph covers an interval of 8 hours from 11.20 a.m. to 19.20 p.m.

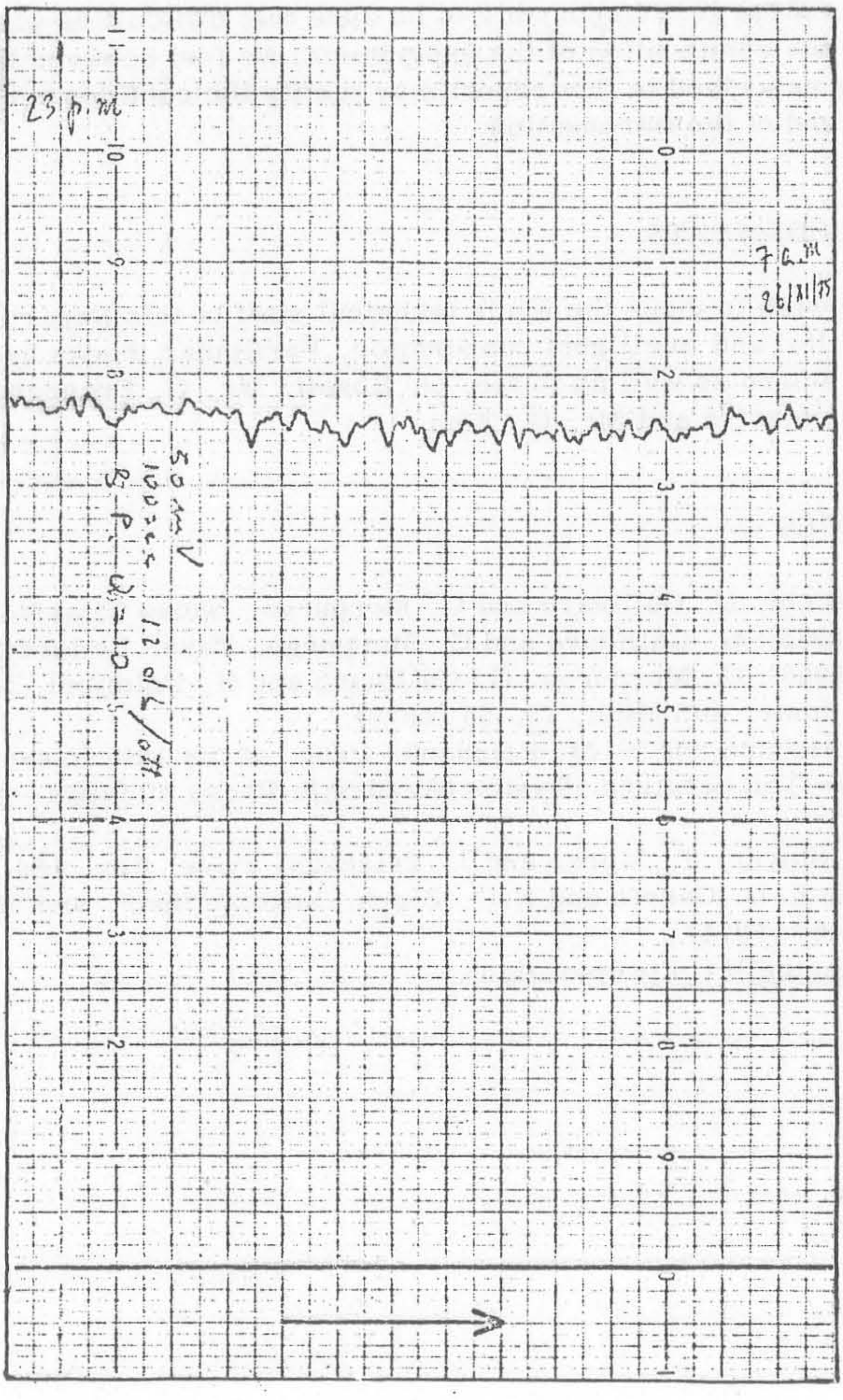

FIG. 8 - The same as for the figure 7 but during an interval of 8 hours at night (23 p.m. to 7 a.m.).

been reached when the plot of Fig. 8 was done).

Of course it is impossible to be sure that difficulties will not emerge in the continuation of the experiment; we feel however that the results described in this report may justify the confidence expressed at the end of the introduction.

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