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I. Modena and F. Scaramuzzi: TECHNICAL ASPECTS OF THE MEASUREMENT OF IONIC CURRENTS IN LIQUID HELIUM. -

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INTRODUCTION.

Measurements of ionic currents in liquid He^3 and He^4 have recently been made in many laboratories.

Besides the macroscopic information (mainly deduced from the mobility) that these measurements give about any liquid, when dealing with quantum liquids such as He^3 and He^4, the ions can be regarded as easily identifiable microscopic probes which do not materially perturb the system; then, for these liquids, it is possible to obtain information, sometimes only qualitative, about their microscopic structure. As an example, information regarding the thermohydrodynamics of He^4 II has been obtained[1-7].

The authors' aim is to review the techniques connected with these measurements. This paper is divided into two main parts: In the first, the general technical aspects pertaining to the measurements performed will be described; the second will provide a description of the main measurements performed so far.

I. - GENERAL TECHNICAL FEATURES.

A. - Construction of the Cells.

The experimental cells are generally ionization chambers, supplied with ion-generating electrodes (see B), collecting electrodes, and sometimes guard electrodes and grids.

Figs. 1 and 2 show the details of two experimental cells. A simple cell, used to measure the mobility of He^3 under pressures up to 20 atm with a He^3 refrigerator (down to 0.39°K)[8] is shown in Fig. 1. A more sophisticated cell, which has been used for measurements of ionic currents in rotating superfluid helium[6,7], is shown in Fig. 2.

Since only very small currents are normally obtained (10^{-8}-10^{-16} A), and the input impedances of the measuring instruments are very high (up to 10^{12} ohms), it is very important to have a very high insulation resistance between the electrodes themselves and between them and ground. This resistance must be large ($\sim 10^2$ times) in comparison to the input im

2.

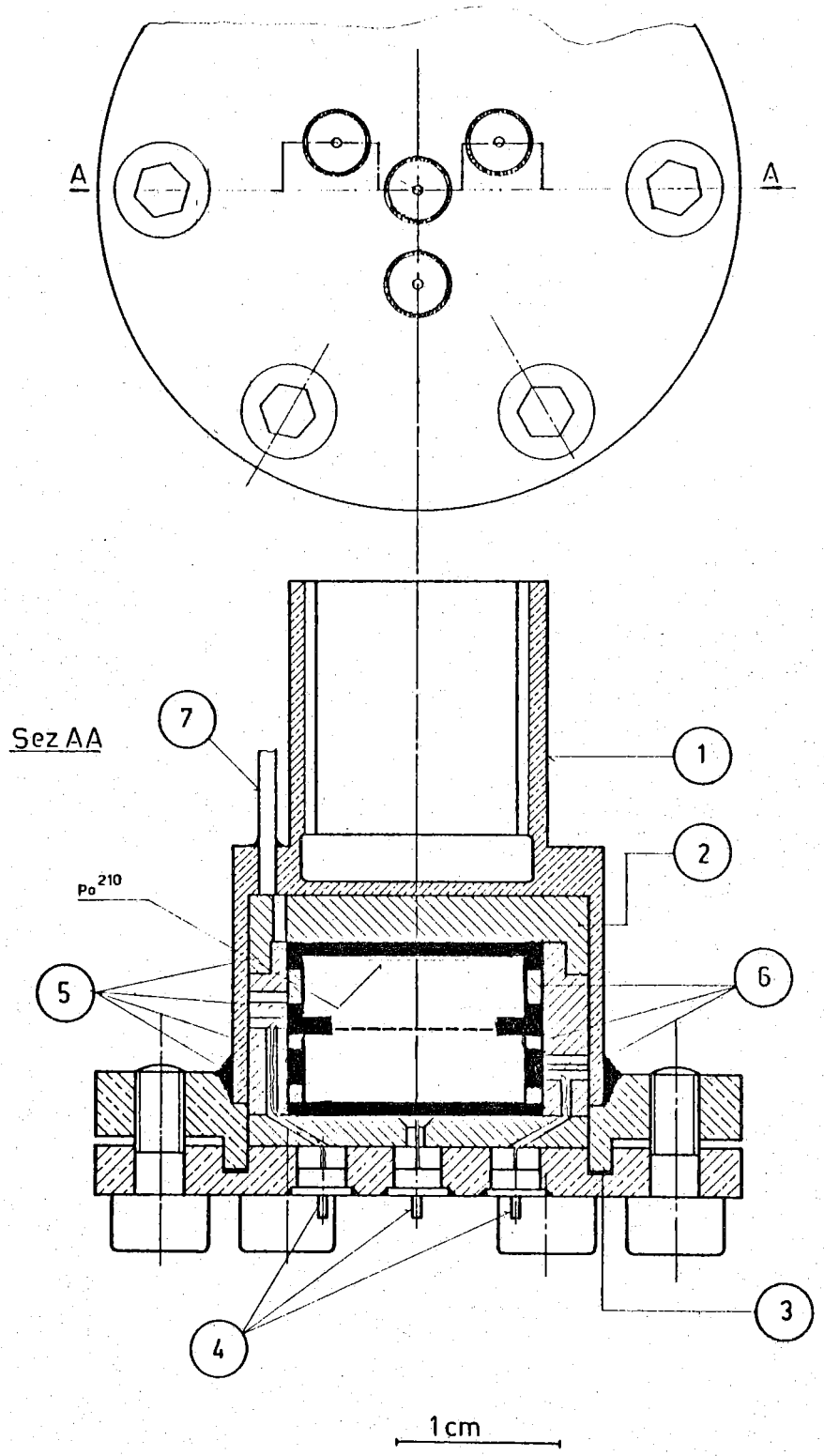

FIG. 1 - Cross section of a cell used to measure the mobility of He^3 down to temperatures of 0.39°K (with a He^3 refrigerator[8]). It consists of four electrodes 5. Starting from the top, these are: an ion-generating electrode with a polonium source deposited on it, a grid, a guard electrode and a collecting electrode. 1 is the copper case whose upper part screws into the He^3 refrigerator. 2 is the plexiglass case which holds the cell: it has holes in it to permit the He^3 coming through capillary 7 to fill the experimental space. 6 are plexiglass rings which act as spacers and insulators between the electrodes. 4 are kovar-glass vacuum seals for the electrical leads. 3 is an indium ring which ensures a perfect vacuum seal at low temperatures.

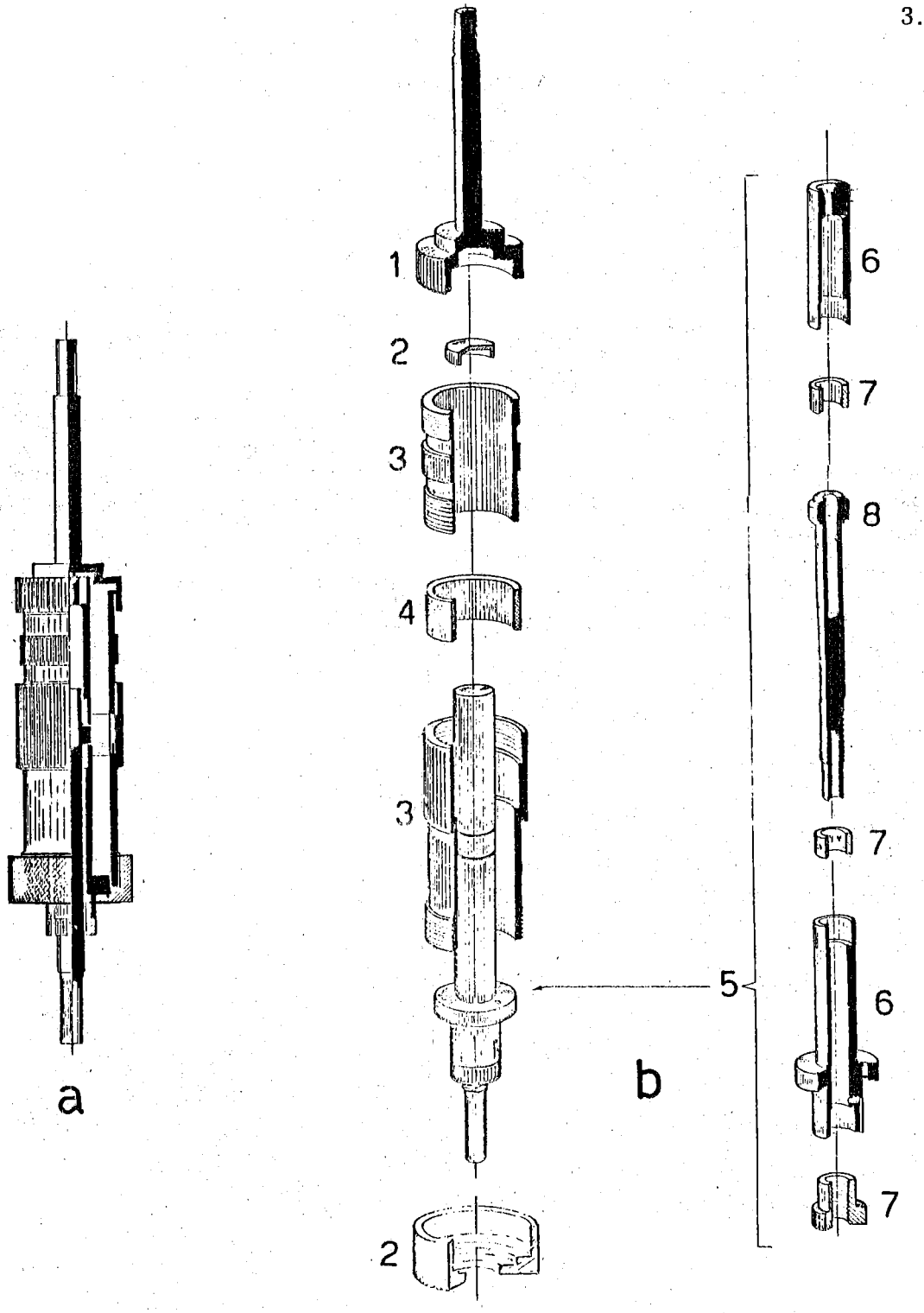

FIG. 2 - Cell used for ionic current measurements in rotating superfluid helium. The whole assembly is shown in a. Two successive exploded views are shown in b. The cell consists of a cylindrical diode. The external electrode consists of a ring 4 covered on the inside with polonium. It is held by the system of rings 3. The cap 1 of this electrode is connected to the rotational axis, which also acts as the applied voltage lead. The central ensemble 5 is held in position and insulated from the external electrode by plexiglass spacers 2. An exploded view of the central ensemble 5 is shown on the right hand side of Fig. 2. 8 is the collecting electrode, 6 are two guard electrodes, insulated from 8 and held in place by three plexiglass insulators 7. The tail of 8 extends from the whole assembly (see a) and is connected to the electrometer as shown in Fig. 7.

pedance. Materials normally used to obtain such good insulation are perspex, araldite, distirene, teflon, glass, etc.

Another requirement of these cells is the necessity that the electrode surfaces be perfectly conducting: The presence of insulating zones prevents an accurate calculation of the effective surfaces (emitting and collecting), and the accumulation of electric charges on these surfaces alters the electric field distribution; hence, in practice, the currents are altered and long transient effects are present. This difficulty can be avoided by the use of noble metals (silver, gold or platinum) for the electrodes. When the electrodes have non-simple geometries, some authors made them out of easily obtainable and easy-to-work metals (copper, brass) coated (by evaporation or electroplating) with silver or gold. One of us (F. S.) successfully used brass electrodes coated with nickel first and rhodium afterwards. Arkipov and Shal'nikov[9, 10] used electrodes of molybdenum and tungsten.

Another difficulty that sometimes occurs in devices of this type is the accumulation of static charges on the surfaces of the insulating materials exposed to the ion beam, and this has the effect of altering the electric field. This happens, for example, in the zone separating two collecting electrodes. This difficulty has been overcome by Careri and coworkers by the use of electrodes which are thick (2 to 3 mm) in comparison with the distance (0. 2 to 0. 5 mm) between them (see Fig. 3a): In this way the field intensity in the gap between the electrodes rapidly decreases in going towards the insulator, so that it is highly improbable that very many ions reach the surface of the insulator. Another method has been used by Bartoli and Scaramuzzi and is illustrated in Fig. 3b, which is self-explanatory.

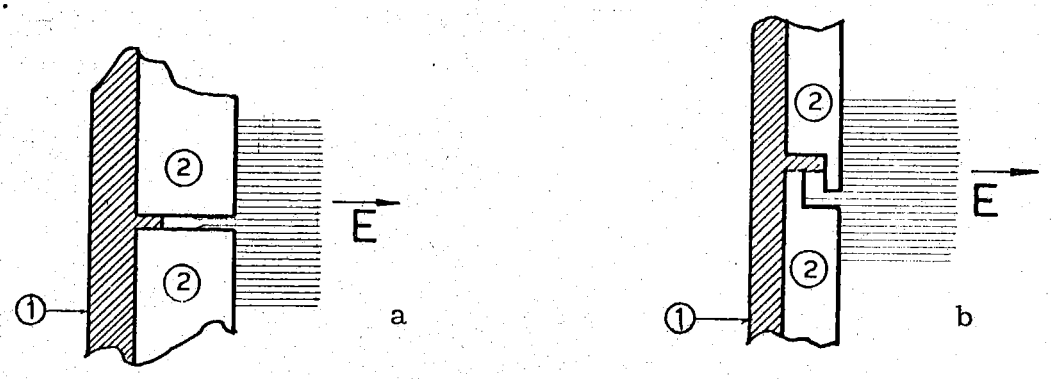

FIG. 3 - This Figure shows two methods employed to avoid charge accumulation on insulating surfaces separating the electrodes. 1 is the insulator. 2 are the electrodes. What is done, essentially, is to place the insulators in a region where the electric field intensity is much lower than in the experimental space.

We just want to mention here the possibility of using guard electrodes when boundary effects must be avoided.

B. - Ion Generators.

The production of ions in liquid helium has so far been achieved by means of irradiation by radioactive substances or electron extraction by the photoelectric effect.

The first of these methods is the most frequently used, because it is simpler to achieve and production of ions of both polarities is possible.

Radioactive substances which have been used up to now are tabulated in Table I.

TABLE I

Characteristics of the Radioactive Substances used for ion production in liquid He^3 and He^4 (x)

Radioactive Substance	Radiation	Half life	Energy (MeV)	Range in liquid He^4 (mm)
Po^{210}	α	138 d	5.3	$\sim$0.2
Pm^{147}	β	2.26 y	0.23	$\sim$0.2
H^3	β	12.5 y	0.018	$\approx$ 0.005
Co^{60}	γ	5.25 y	$\swarrow$ 1.17 $\searrow$ 1.33	---

(x) Data regarding energy and half-life are taken from the "Handbook of Chemistry and Physics", 42nd edition.

Co^{60} has been tentatively used in only one case (Careri and coworkers, 1956), irradiating the cell from the outside of the cryostat with the aid of a collimator. This method was soon abandened because of the weak currents due to the insufficient ionization that could be obtained with easily-handled sources (up to 50 mC), and also because of the necessity for well-defined and localized ion sources.

Po^{210}, used by most experimenters, emits alpha-particles (and, in a ratio $1/10^6$, gamma-rays, whose effect is absolutely negligible). The range of these alpha-particles in liquid He^4 is $\sim$ 0.2 mm, so a Po^{210} source creates a layer $\simeq$ 0.2 mm thick of highly ionized liquid helium. With an electric field of the proper sign, it is possible to draw out of the external surface of this layer ions of the desired sign, this surface acting as an ion source. For sufficiently intense sources, the electric field presumably does not penetrate into this layer, and as a consequence, the effective distance between the electrodes is $\sim$ 0.2 mm less than the geometrical distance. Evidence for this effect has been found by Bartoli and Scaramuzzi

Gaeta[12] used a beta-source of Pm^{147}. The characteristics of this source are very similar to those produced by alpha-emitters. The main

difference is the difficulty of obtaining very intense sources with Pm^{147}.

Archipov and Shal'nikov[9, 10] used as the ion source a thin layer of Zr or Ti (0.5 μ) treated with tritium and applied to a polished tungsten or molybdenum plate. The source so obtained was then coated with a layer 0.1 μ thick of platinum. Under these conditions, the range of the beta-particles in liquid He^4 is 5 μ.

It is necessary to have an intense radioactive source (alpha or beta) in order to obtain an intense ion source. However, a general and simple relation between the intensity of a radioactive source and the intensity of the corresponding ion source does not exist. Furthermore, it is not easy to define the intensity of the ion source itself. One criterion could be the measurement of the current density for a given geometry and a given applied potential. The reason for introducing such an empirical criterion is that space charge effects are present, which prevent any simple analysis of the electric field. Increasing the intensity of the radioactive source, the space charge effects become larger and larger until the condition of "complete space charge limitation", defined by $E = 0$ at the emitter[13], is reached. When this condition applies, the intensity of the ion source is independent of the intensity of the radioactive source and is the maximum attainable. The intensity of the radioactive source for which this condition is valid depends on the value of the potential and increases with it (see Fig. 4). On the other hand, the intensity of the radioactive source itself has an upper limit, due to autoabsorption of the alpha-particles, which makes the deepest layers of the radioactive materials ineffective.

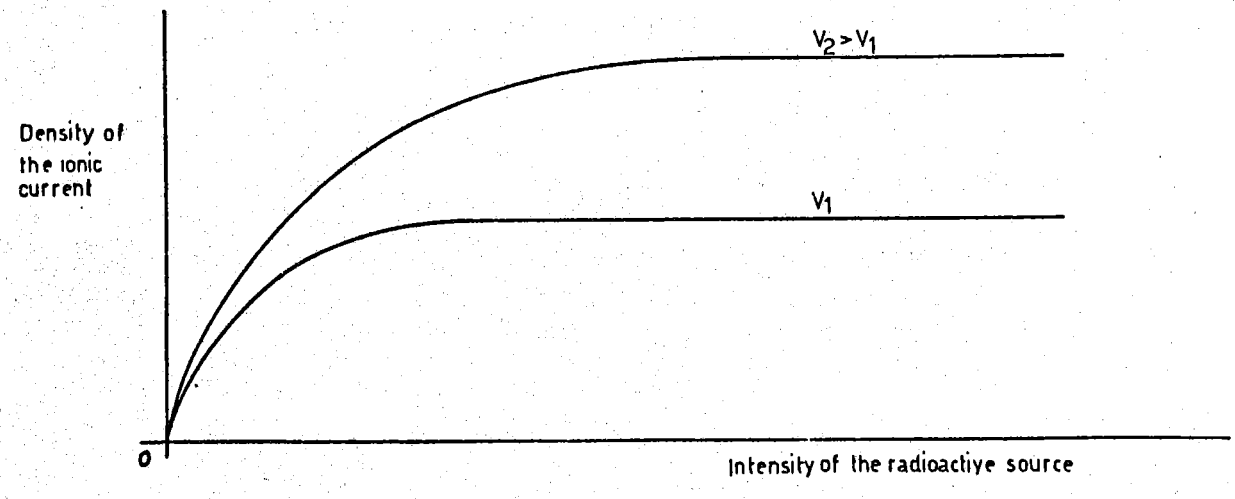

FIG. 4 - Qualitative dependence of the ion source intensity (defined by the ionic current density at a given voltage for a given geometry) on the intensity of the radioactive source. Saturation is reached when the condition of "complete space charge limitation" is fulfilled. The value of the radioactive source intensity at which saturation occurs increases with voltage.

Po^{210} and Pm^{147} can be obtained commercially in the form of salt solutions. For example, the "Radiochemical Centre"(x) sells Po^{210}

(x) UKAEA, Radiochemical Centre, Amersham, Buckinghamshire, England

as polonium-chloride in hydrocloric acid or as polonium-nitrate in nitric acid and Pm^{147} as promethium-chloride in hydrocloric acid; the solutions are of any desired dilution.

For Po^{210}, the simplest way to make a source out of an electrode is autodeposition, which is based on the difference in the contact potentials between the radioactive element and the element which constitutes the electrodes. Careri and coworkers have used this method often, obtaining good results with silver electrodes and a solution of polonium nitrate in nitric acid (1N). The area to be covered with the radioactive substance is marked off by coating the rest of the electrode with a substance that cannot be attacked by the radioactive solution and that can be easily removed (varnishes such as glyptal have been used or paraffin). The electrode so prepared is directly immersed in the solution and left there for a time, varying from a few minutes to one day, depending on the amount of polonium to be deposited. When dealing with small plane surfaces, one can deposit a few drops of the solution on the area of interest.

Also the method of electroplating is normally used and is preferable when very intense sources are desired. The electrolysis is accomplished by connecting a platinum plate to the anode and the electrode (to be plated) to the cathode.

After carrying out one of the procedure suggested above, the electrode still has two important defects:

a) The surface in general is not perfectly conducting, because of oxide formation;

b) Po^{210} is particularly volatile, and so the surfaces facing the radioactive electrode will be contaminated by the radioactive element and will become ion sources themselves.

These defects can be avoided by coating the source with a layer of a noble metal, whose thickness is less than the range of the alpha-particles in question. At Frascati, for example, layers of gold and of copper+rhodium have been deposited over polonium sources. The results were not completely satisfactory in the case of very intense sources, although in this case it is probable that the first defect (formation of oxides on the surface) can be neglected: In fact, one would expect that the layer of highly ionized liquid behaves like a conductor, short-circuiting the insulating areas.

Careri and coworkers measured the uniformity of the radioactive sources by counting, for a proper geometry, the alpha-particles emitted. Over linear dimensions of the order of 1 mm this was found to be rather unsatisfactory: Deviations of the order of 30% were found. Over larger linear dimensions the nonuniformity decreases. Probably this nonuniformity does not correspond to an equivalent nonuniformity of the ion source, since only a very small part of the ions are extracted from the ionized layer. Experimental information on the subject is lacking.

It is useful to mention here the dangers connected with the handling of polonium. It is classified as "very toxic" in the international clas-

sification concerning the toxicity of radioactive substances. Also it is very dangerous because of its high volatility. Therefore the preparation of a source requires the use of very efficient safety equipment. An important warning concerning also the use of already prepared sources: In order to avoid abnormal and dangerous evaporation, these should not be heated (by soldering, for example).

It may help the reader to know that it is possible to commercially obtain electrodes which have already been plated with polonium. The "Radiochemical Centre"(x), for example, supplies sources of any desired shape and intensity (up to 10 mC/cm^2 deposited) and covered (on request) with a thin gold layer.

An example of the successful extraction of electrons from a photocathode in liquid helium is given in the article by Dahm et al.[14]. Unfortunately, no information about the technical details is given. Also Arkipov & Shal'nikov[9] succedded in extracting electrons from a zinc electrode in liquid helium.

C. - Current Detection.

The devices most frequently used for the detection of ionic currents are vibrating reed electrometers, which are built commercially by many firms. In Table II the characteristics of some of the most widely used types are listed. The use of these instruments, which are able to detect direct currents down to 10^{-17} A, does not require particular care, except for the highest sensitivities, where it is necessary to have, in addition to a very high insulation resistance of the current leads, effective electric shielding of the whole system. Furthermore, in this case, it is preferable to connect the electrometer head to the apparatus with a shielded rigid cable. The response time of these electrometers depends on the input resistance which, in the most common types, can be varied among several different values. For the maximum sensitivity ($\sim 10^{12}$ ohms), the response time is of the order of a few seconds, so these instruments are not suitable for the measurement of rapidly varying currents. However, in those cases when only the average value of a periodic current is of interest, it is still possible to use instruments of this type, by using proper RC integrators in the input (see Fig. 5). When the shape of the signal must be determined, the signals are amplified with an a. c. amplifier, and the output is displayed on an oscilloscope[14,15].

The connections between the electrometer and the cell are usually made with shielded leads. The shields are normally thin-walled (0.1 to 0.2 mm) tubes of stainless steel or german silver (or similar alloys), while the lead can be a thin wire of copper, manganin, or some other similar alloys. Use of such alloys permits the use of thicker wires, which are easier to handle. The space between shield and lead is under vacuum, and the lead is held in the center of the shield by means of insulating spacers (made of di-

(x) See footnote at page 6

TABLE II

Main characteristics of the electrometers most widely used for ionic current measurements

Electrometer type	Maximum sensitivity (full scale)	Input resistance ohm	Time constant
EKCO(1) N616B	3×10^{-15} amp	10^8, 10^{10}, 10^{12}	0.1 sec for 10^8 ohm 0.5 sec for 10^{10} ohm 1.0 sec for 10^{12} ohm
CARY(2) 31MS	3×10^{-15} amp	$10^7 \div 10^{12}$	10^{-2} sec for 10^8 ohm 0.1 sec for 10^{10} ohm 10 sec for 10^{12} ohm
VIBRON(3) 33C	1×10^{-14} amp	up to 10^{-12}	30 sec for 10^{12} ohm
KEYTHLEY(4) 610A(x)	1×10^{-13} amp	$10 \div 10^{14}$	---
E-h(5) 201B(x)	3×10^{-14} amp	$10^6 \div 3 \times 10^{12}$	40 μsec for $i=10^{-6}$ amp 250 μsec for $i=10^{-9}$ amp 0.4 μsec for $i=10^{-12}$ amp 5 μsec for $i=3 \times 10^{-14}$ amp

(x) Not of the vibrating reed type.

(1) EKCO Electronics Ltd., Southend-on-Sea, Essex, England

(2) CARY Instr. Appl. Ph. Corp., 362 W Colorado St., Pasadena 1, California, USA

(3) VIBRON Electronic Instr. Ltd., Richmond, Surrey, England

(4) KEYTHLEY Instr., Cleveland 6, Ohio, USA

(5) E-h Research Lab., 1922 Park Blvd., Oakland 6, California, USA.

stirene, plexiglass, glass, etc.). To compensate for the difference in thermal contraction between shield and lead, one of the lead terminals consists of a small spring (made, for example, of steel) and is mounted under moderate tension.

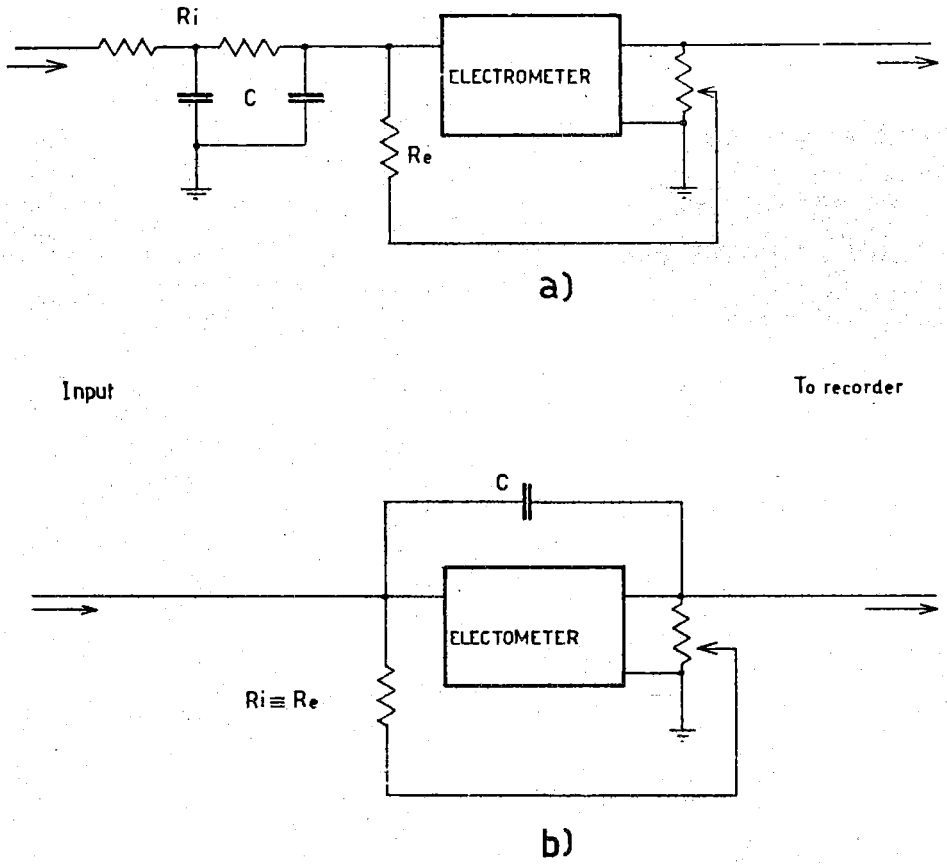

FIG. 5 - Two examples of RC integrating circuits used with electrometers to detect the average value of a periodic current. In a the integrator is completely external to the electrometer. In b the input resistance of the electrometer is used as the resistance element of the integrator.

Careri and coworkers have successfully used connections consisting of two concentric stainless steel or german silver tubes (outer diameters 1 and 4 mm), held apart by insulating plexiglass washers located about 10 cm from each other. One of us (I. M.) has constructed a multiple shielded cable (with eight leads), whose design is illustrated in Fig. 6.

The ends of these cables are closed by highly insulated vacuum seals, the ones most commonly used are made with kovar and glass and are easily available commercially. However, not all the commercially available types have insulation resistances high enough for high sensitivity measurements. Furthermore, some types have lambda-leaks, or they break under thermal shock. Many authors describe those made by Stupakoff(x) as being

(x) Stupakoff, now Carborundum Co. , Latrobe, Penns. , USA

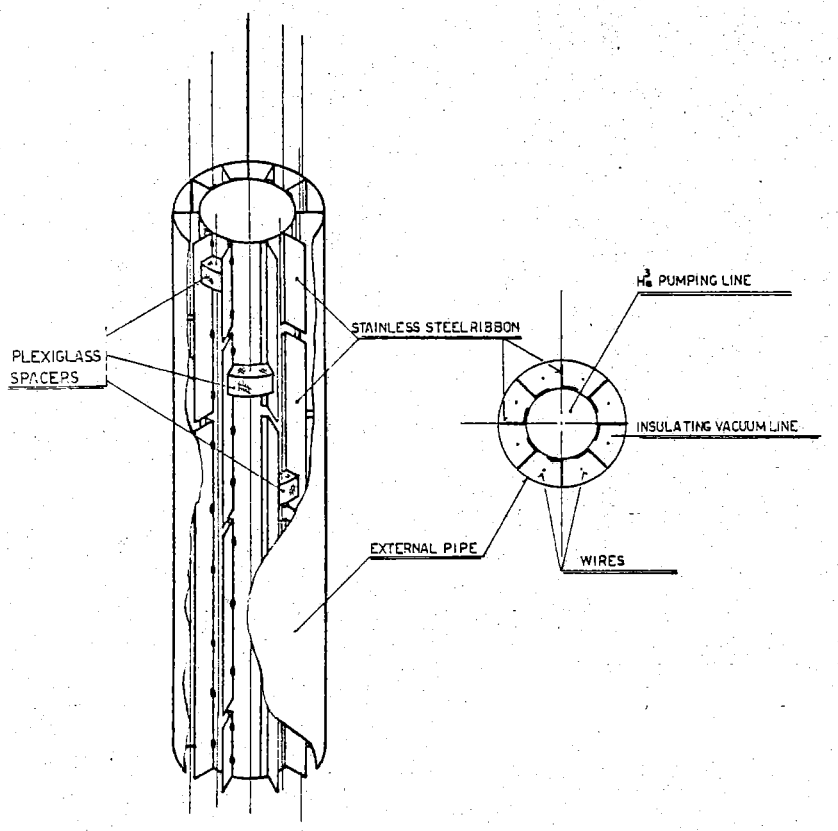

FIG. 6 - This shows a shielded multiple cable, containing eight leads, which are shielded from each other and from the outside. Plexiglass spacers ensure proper positioning of the leads. The L-shaped stainless steel ribbon, which act as the shield between the leads, is soft soldered to the internal tube at various points; it is made of short pieces (≃ 8 cm long) in order to reduce thermal conduction. The external tube is completely independent of the rest of the assembly: it can be easily mounted and dismantled, since it is coupled to the rest of the cable by only one O-ring system at room temperature. The external pipe constitutes the insulating-vacuum case for a He^3 refrigerator. This system has the advantage that it does not require any electrically insulated vacuum seal between the He^4 bath and the insulating-vacuum space.

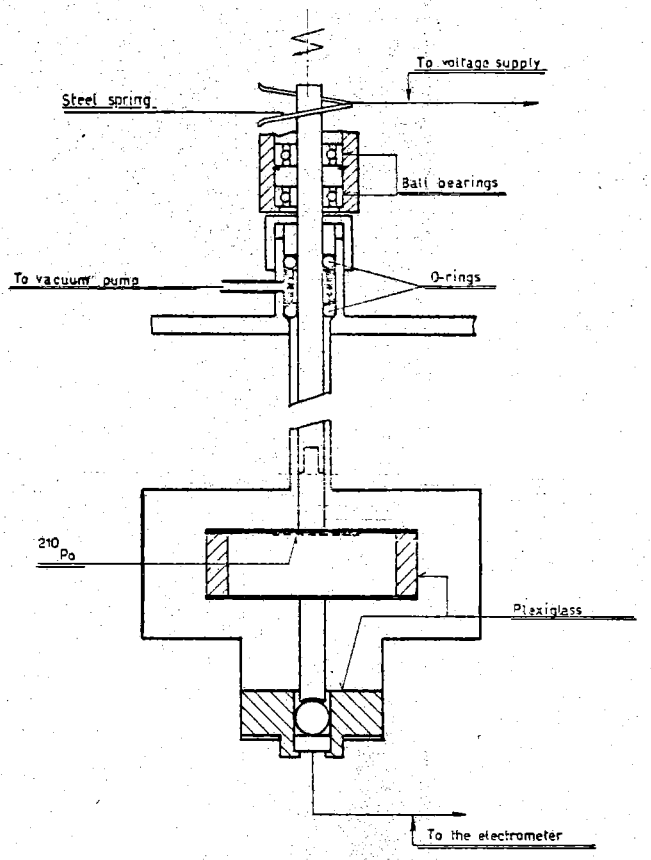

FIG. 7 - Schematic view of a sliding contact system used for ionic current measurements in rotating helium[6,7]. The cell can be interchanged (for example, the one shown in Fig. 2 has been used). The two leads are the two ends of the rotational axis extending above and below the cell. The top of the axis has a sliding contact, made of a V-shaped piece of steel wire, located outside of the cryostat, and this in turn is connected to the voltage supply. The bottom end of the axis has a concave surface which rests on a steel ball, connected to the electrometer: this ensures good positioning of the axis and minimizes friction. A system of two O-ring ensures a vacuum seal. The pumping line between the two O-rings is a further precaution to prevent air frosting, which would prevent rotation. Two ball bearings are located at the top to ensure good centering of the rotational axis.

particularly suitable for use with liquid helium. The authors of this paper also used the seals made by Electrovac[x] with success. In a few laboratories, simple types of insulating vacuum seals have been constructed[16, 17].

Brown and Borfield[18] made a special coaxial cable by silvering the internal and external surfaces of a pyrex tube, with the lead inside the tube. In this way they obtained double shielding, suitable for measurements in which the inner shield is not grounded.

A particular problem related to the measurement of currents in a rotating cell has been solved by Careri and coworkers (see Fig. 7). A vacuum-tight rotating shaft has been constructed (using a system of O-rings), where the rotating shaft is used for one of the leads with a sliding contact outside the dewar. The lower end of the cell consists of a small cylinder having a concave surface which rests on a steel ball: this ensures good centering of the rotating system, with negligible friction and good electrical contact.

II. - EXPERIMENTS INVOLVING THE MEASUREMENT OF IONIC CURRENTS IN LIQUID HELIUM.

The simplest measurement that can be imagined is the voltage-current characteristic of a diode, where one of the electrodes is the ion-generator and the other is the collector. Usually the ion-generator is connected to the voltage supply and the collector to the electrometer. In this way, ions of the same sign as the applied potential will move in the experimental region. Guard electrodes are used to guarantee uniformity of the electric field.

Due to space-charge effects, which prevent a simple description of the physical situation in terms of only the mobility, the analysis of such a measurement is difficult in general.

A special case in which it is possible to solve this problem exactly is that of "completely space charge limited currents", defined by the condition that the electric field vanish at the emitter. In this case, it is possible to derive the following simple relation between the current and the applied potential[13]:

$$i = a\mu V^2,$$

where μ is the mobility of the ions, and a is a constant factor which depends on the geometry of the system. This equation suggests one possible way to measure ion mobilities simply[11]. The method is limited, at the highest mobilities, by the difficulty of making ion sources intense enough to obtain complete space charge limitation. In fact, by this method, Bartoli and Scaramuzzi[11] were only able to measure the mobility (which increases very rapidly for decreasing temperatures) of positive ions in superfluid He^4 in the range 2.18°K to 1.2°K, i.e., up to $\mu = 2$ cm^2/v. sec.

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[x] Electrovac, Rampengasse 5, Wien XIX, Austria.

This method appears to be suitable for the measurement of the mobility of classic liquids, which is generally a couple of orders of magnitude less.

The mobility is undoubtedly the most significant physical quantity in the measurements we are dealing with, and different authors have measured it by different methods, most of them based on measurement of the time of flight τ of the ions between two electrodes in the presence of an electric field E:

$$\mu = \frac{v}{E} = \frac{d}{\tau E} ,$$

where v is the ion drift velocity, d is the distance between electrodes.

Williams[15] was the first to measure the mobility of ions of both signs in liquid He^4 at high electric fields (from 4 to 130 KV/cm). His method consisted of the detection on an oscilloscope of the current pulses due to the ions of one sign, produced along the path of a single alpha-particle, and drawn to one electrode by the d. c. electric field. The apparatus consists of a diode, in which one of the electrodes contains the polonium source. The duration of the current pulse, which corresponds to the time of flight of the ion cloud between the two electrodes, is measured. To obtain an accurate measurement, it is necessary that the range of the alpha-particles be much less than the distance between the electrodes. Experimental conditions made it necessary for Williams to use electrodes which were very close together (the distance varies between 0. 15 and 0. 44 mm, i. e. , it is of the order of the alpha-particle range). So, in general, the current pulse contains contributions from ions of both signs. However, when the alpha-paths are nearly parallel to the surface of the emitter, the pulse is due to ions of one sign only. Williams has selected, from all the pulses recorded on the oscilloscope screen, only these cases.

A very similar method has been employed by Dahm et al.[14] in the measurement of the mobility of electrons abtained by photoemission. They use electric fields ranging from 1500 to 2600 V/cm. The current pulse was obtained by a light flash incident on the photocathode.

Both Williams and Dahm et al. worked with high electric fields, the former in a range in which the mobility depends on the electric field. Meyer and Reif[19] applied a method, used by Tyndall and Powell[20] for gases, to liquid helium for the measurement of the ion mobility at low electric fields ($E \leq 200$ V/cm). The apparatus (see Fig. 8) consists of six electrodes: the ion-generator (with a polonium source), the collector and two pairs of grids. A homogeneous d. c. electric field is applied between the generator and the collector. A sinusoidal voltage is superimposed between each pair of grids (in a later paper[21] a square wave signal was used), which alternatively opens and closes these "shutters" to the passage of ions. When the period of the signal, or a submultiple of it, equals the time of flight of the ions between the shutters (more precisely , between grids A and B), the ions can reach the collector and a current is observed. A plot of the current versus the frequency of the alternating signal exhibits maxima at multiples of the fundamental frequency, whose

period equals the time of flight. Meyer and Reif measured up to 10 maxima. The absolute value of the mobility is affected by the error with which the distance between the two shutters is known. In the more recent measurements, the mobility values are given within 5%. Measurements have

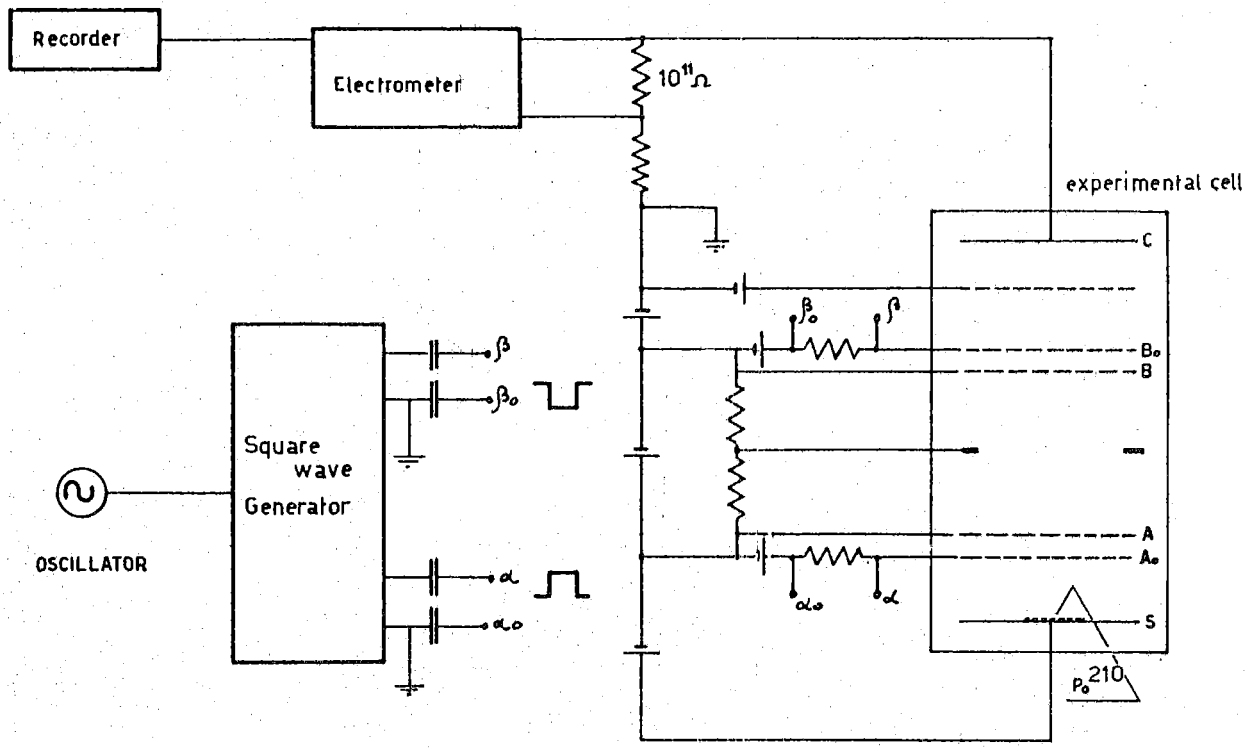

FIG. 8 - Schematic view of the cell used by Meyer and Reif[19,21,22] and by Davis et al.[23] to measure ionic mobilities in liquid He^3 and He^4. The time of flight of the ions between grids A and B is measured. The two pairs of grids AA_o and BB_o act as shutters with regard to the passage of the ions. A block diagram of the electric circuit is also shown.

been obtained for ions of both signs, at temperatures ranging from 4.2°K to 0.5°K for He^4[19,21,22], and from 3.4°K to 1.0°K for He^3 by Davis et al.[23]. The cell is enclosed in a metal box, able to withstand rather high pressures (up to 15 atm).

Cunsolo[24] set up a method, also based on measurement of the time of flight, which requires much simpler apparatus. The cell consists of only three electrodes: an ion-generator (with polonium source), a grid, and a collector. A cell of this kind is shown in Fig. 1. A d. c. electric field is applied between emitter and grid, and to this is superimposed a square wave voltage V between grid and collector. During one half-period of the square wave, the ions travel from the grid (which acts as ion source) towards the collector, in the following half-period they return towards the grid. A current will reach the collector only if the time of flight is less than one half-period. In the first approximation, the average current measured is

$$\bar{i} = \frac{i_o}{2}\left(1 - \frac{\tau}{\theta}\right) \quad \text{for} \quad \theta \geq \tau \quad ,$$

$$\bar{i} = 0 \qquad \text{for } \vartheta \leq \tau \ ,$$

where

$$i_o = \varsigma \mu \frac{V}{d}$$

is the value of the current measured by applying a constant voltage V between grid and collector, τ is the time of flight, and ϑ the half-period of the square wave. $\bar{i}$ is obtained by integrating the input signal to the electrometer with an RC circuit ($RC \gg \tau$). In practice one measures, for a given V, the current as a function of the frequency (with $\vartheta \geq \tau$) and extrapolates the straight line $i\,(1/\theta)$ to $i = 0$. The value of ϑ so obtained equals τ.

This method has been used by Careri, Cunsolo and Mazzoldi[25] and by Cunsolo and Mazzoldi[26] for the measurement of the mobility of ions of both signs in He^4 II(x) at temperatures down to 0.85°K and pressures up to 25 atm. Furthermore, this method revealed discontinuities in the mobility as a function of the electric field, corresponding to ion drift velocities which are multiples of a fundamental critical velocity. These have been attributed to the creation of a new kind of excitation in the superfluid.

One of us (I. M.) used this method to measure the ion mobility in liquid He^3 at temperatures ranging from 3.2°K to 0.39°K and pressures up to 20 atm, with fields less than 450 V/cm[8, 27].

In He^4 II the motion of the excitations can be investigated by the measurement of ionic currents, using the ions as microscopic probes. The first such experiment was successfully performed by Careri, Scaramuzzi and Thomson[2] for the purpose of demonstrating that the extraneous particles participate in the motion of the normal fluid (i. e., of the excitations) and not in the motion of the superfluid. (This had already been demonstrated by Daunt et al.[28] and by Lane et al.[29] for He^3 impurities). The cell, which is shown schematically in Fig. 9 consists of an emitting electrode, containing a zone covered with polonium, and four collecting electrodes facing the former. A heater at the bottom of the cell can supply heat, which gives rise to a counterflow of superfluid and normal fluid. The dashed lines show the path of the ions under the effect of a stationary electric field E in the absence of heating. When the heater is turned on, electrode 2 shows an increase in current, and at the same time electrode 4 shows a current decrease, thus proving that the ions follow the motion of the normal fluid. This experiment is also quantitative, because it demonstrates that the component of the ion drift velocity along the axis of the channel equals the normal fluid velocity, which is known from other experimental data.

(x) For an explanation of the concepts of He^4 II, excitation, superfluid, normal fluid, etc., see, for example: K. R. Atkins, "Liquid Helium" (Cambridge Univ. Press, 1959); C. T. Lane, "Superfluid Physics" (McGraw Hill, New York, 1962).

For large heat inputs, this cell exhibits an anomalous behaviour for negative ions only. This has been attributed to turbulence, and it has been possible to measure the threshold for this phenomenon[3].

Later, a more sensitive method was found[5] to measure the turbulence threshold, consisting of the measurement of the total change in current in a simple diode. Once more, although positive ions do not feel this change of hydrodynamical regime, the negative currents decrease considerably.

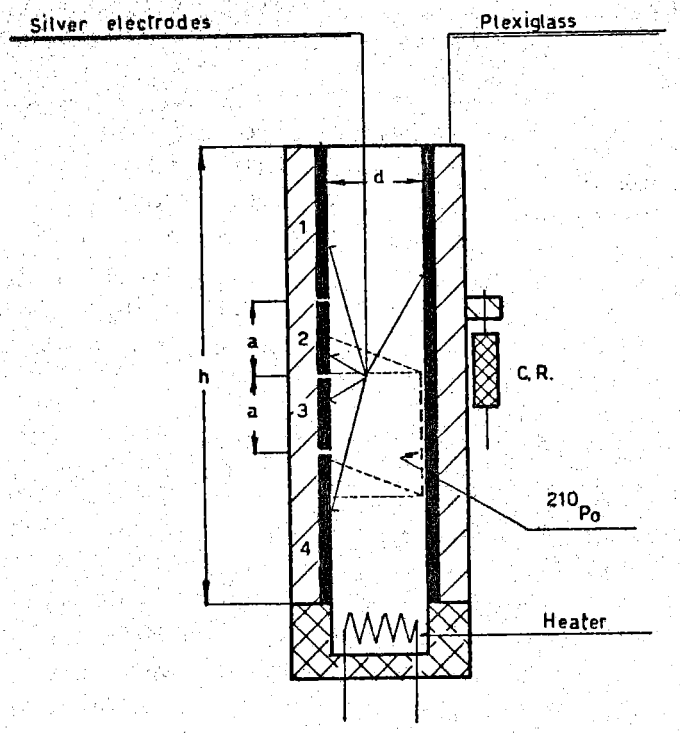

FIG. 9

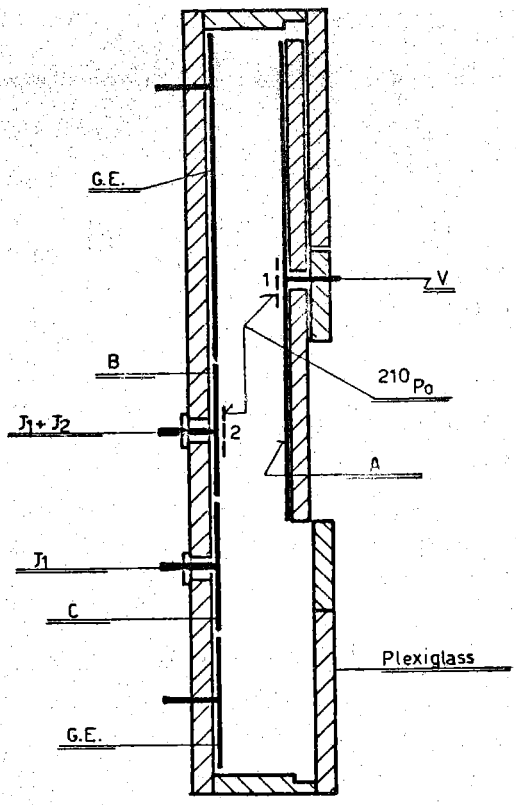

FIG. 10

FIG. 9 - Schematic view of the cell used for "heat flush" experiments[2,3]. Four independent collecting electrodes, indicated by 1, 2, 3, 4, can be connected to electrometers. Heating the helium at the bottom of the cell makes the superfluid move towards the heater and the normal fluid moves in the opposite direction. The resulting current increase on electrode 2 and decrease on electrode 4 indicates that ions are dragged by the normal fluid. The horizontal and inclined dotted lines show the ion beam path without and with heating, respectively (for the sake of clarity, the effect of heating is exaggerated).

FIG. 10 - Schematic view of a cell used to measure the volume recombination coefficient of ions in superfluid helium[30]. It is essentially a diode with ion sources on both electrodes. It is possible to measure the current, due to the sum of the two ion beams, as a function of the vertical distance between the positions of the ion sources. This distance can be varied by moving electrode A, which can slide in a direction perpendicular to the electric field. When the sources are superimposed, a decrease in the total current can be observed, due to ion recombination.

Finally, the same type of phenomena has been observed by Careri, McCormick and Scaramuzzi[6,7] in a rotating diode, when the negative ions move perpendicularly to the rotational axis, thus indicating an analogy between the two hydrodynamical situations. We want to point out here that

the fact that negative ions are able to detect the presence of different hydrodynamic situations, probably consisting of collectively excited states of the superfluid, indicates an interesting direction for the development of ionic current measurements in superfluid helium.

Careri and Gaeta[30] have measured the volume recombination coefficient for ions in liquid He^4. They find a temperature dependence which can be expressed in terms of the theory of Langevin. The experimental cell consists (see Fig. 10) of a diode with polonium deposited on both electrodes in very well-defined zones and with the same intensity. In this way, ions of both signs move simultaneously in opposite directions in the helium. By sliding electrode 2 in a direction perpendicular to the electric field E, the two ion beams will be superimposed. The resulting decrease in total current will give a measurement of the recombination coefficient.

Careri, Duprè and Modena[31] have measured the mobility of He^4 at $\sim 0.2^{\circ}K$ by a method due to Townsend[32], based on the deflection of an ion beam by a magnetic field B, which is perpendicular to the electric field. In a dense medium, the beam follows a straight trajectory at an angle ϑ, with respect to the direction of the electric field given by

$$\tan \vartheta = \frac{\mu B}{10^8}$$

(μ in $cm^2/v.\,sec$, B in gauss). Fig. 11 shows schematically a section of the cell. The magnetic field is perpendicular to the plane of Fig. 11. It is possible to calculate the angle ϑ, knowing the ratio of the currents collected on electrodes 1 and 2, with and without magnetic field. A magnetic field of $\sim 2 \times 10^4$ gauss and electric fields of a few V/cm have been used. An adiabatic demagnetization cryostat has been employed to reach the temperature of $0.2^{\circ}K$.

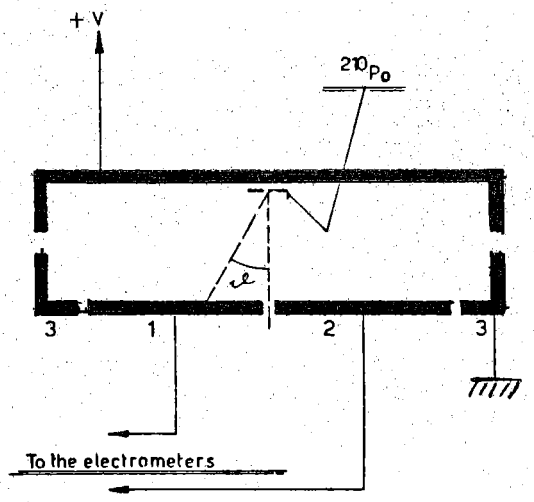

FIG. 11 - Schematic view of the cell used[31] to measure the mobility of ions in superfluid helium at very low temperatures ($\sim 0.2^{\circ}K$) by Townsend's method. A magnetic field perpendicular to the plane of the Figure is applied. The apparatus has cylindrical symmetry about the vertical axis. Electrodes 1 and 2 are semi-circles, surrounded by a guard ring 3. The ratio of the currents collected on electrodes 1 and 2 varies with the magnetic field and permits the calculation of the mobility. The angle of deflection ϑ is simply related to the magnetic field.

Fasoli, Gaeta, Scaramuzzi and Thomson[33] studied the possibility of utilizing the temperature dependence of the current in a diode to set up an ionic thermometer. A simple empirical relation has been found between the current and the temperature, for a constant applied voltage. The sensitivity of such a device proved to be satisfactory from $\simeq 1^{\circ}K$ to $\sim 1.4^{\circ}K$.

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