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THE RESPONSE OF A LIQUID IONIZATION CHAMBER TO
GAMMA RADIATION AND TO HIGH-ENERGY NEUTRONS AND PROTONS

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ABSTRACT

The ionization current produced in a chamber filled with dielectric liquid, e.g. hexane, has been studied. The chamber has been exposed to gamma rays and to high-energy proton and neutron beams from the CERN accelerators. The experimental results obtained are discussed; it is shown in particular that the QF of an unknown radiation field may be estimated from measurements made with a liquid ionization chamber.

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A. INTRODUCTION

The studies of liquid ionization chambers have been resumed in recent years with the purpose of using them for radiation measurements¹⁻¹⁰).

Blanc et al. have published attractive results concerning the response of a liquid ionization chamber to α , γ and neutron radiation. They arrived at the conclusion that such chambers could be used in particular for the estimation of the quality factor (QF) of the radiation⁵⁻⁷). This conclusion was confirmed by Ladu et al¹⁰).

The studies on the liquid ionization chamber are connected with the studies on the conductivity of high dielectric liquids. Jaffé¹¹⁻¹³) who has worked extensively on this subject, proposed the columnar recombination theory^{*}). There has been much discussion about this theory which is now the one accepted for the mechanism of conductivity of dielectric liquids¹⁷⁻²³). Jaffé found that the ionization current I_{ion} in the irradiated dielectric liquid is the sum of the two components¹¹):

$$I_{ion} = I_s + I_{(HT)}.$$

The I component, which is a function of HT, gives rise to a saturation value^{11,1)}, while the $I_{(HT)}$ is considered as an Ohmic current and is proportional to the applied voltage (HT). For liquids, in contrast to gas ionization chambers, it is not possible to obtain saturation for I_{ion} . Blanc et al.⁵⁻⁷) contributed to the study of the liquid ionization chamber with the following observation: the straight lines

*) The columnar recombination theory has been developed first for dielectric liquids. Jaffé has given to this an extension for the gases¹⁴⁻¹⁶).

obtained in the "Ohmic region" of the ionization curve (Jaffé's formula) for different dose-rates all meet - when extrapolated to the HT axis - at the same point on this axis⁵⁻⁷). The co-ordinates of this point depend on the type of radiation to which the liquid in the chamber is exposed; for different types of radiation all these points line up on the HT axis in the same way as the quality factor. The present paper presents new results obtained with high-energy protons and neutrons which confirms that there is a possibility of measuring the QF with a liquid chamber.

An evaluation of the QF in a mixed radiation field is one of the most interesting problems in high-energy radiation dosimetry. During the last years many attempts have been made to measure the dose equivalent and the QF by using the fact that columnar recombination depends on the linear energy transfer (LET) (Baarli and Sullivan²⁴), (Zielecynski et al.²⁵⁻²⁶). Also the direct determination of the LET spectrum of mixed radiation fields using a tissue-equivalent spherical proportional counter was successful²⁷) (Rossi et al.²⁸⁻²⁹). However, the measurement of QF by collecting a fraction of the charge liberated in a liquid should be more closely related to the effects which produce the dose in tissue than are measurements in gases.

The present paper describes measurements made with a liquid ionization chamber at CERN. Such a chamber has been built in order to study its properties and the relation of its response to the QF of the radiation. Measurements were made with γ -rays from a 50 mg Ra²²⁶-source and high-energy protons and neutrons from the CERN 600 MeV Synchro-Cyclotron (SC) and 28 GeV Proton-Synchrotron (PS).

B. THE CHAMBER AND ITS ASSOCIATED EQUIPMENT

The chamber used in the present work is shown in Fig.1. It is a parallel plate chamber with variable electrode spacing. There is an extra electrode in the chamber which is used for the electrolytic purification of the liquid. The results obtained with this extra electrode will be given below in chapter C. The anode is mounted on a stainless steel screw which has a 1.25 mm pitch. The screw is threaded through the plexiglass wall of the chamber (see fig.1). The spacing of the electrodes varies from zero to 1.5 cm and can be determined with a precision of 20% for a spacing of 0.32 mm and with better than 5% precision for spacings of more than 1 mm. (For small spacings, e.g. 0.32 mm, the necessity of a perfect parallelism between the electrodes is obvious). The parallelism of the electrodes was checked by using a combination of electrical and optical methods and was found to be satisfactory. Special care was used in polishing the electrode surfaces, i.e. collector, guard ring and anode. The electrodes and other metallic components of the chamber are of stainless steel. The main wall was a plexiglass cylinder which carried the anode and the extra electrode. This cylinder is 2 mm thinner in the electrode region and its inner diameter is of 52 mm. The base is made of teflon; the guard ring and the collector are on the same level, separated by 1.5 mm of teflon. To seal the plexiglass cylinder to the teflon base, and also to seal the collector and guard ring to the teflon, an interlocking circular "V" groove and edge were used.

For the measurements of ionization currents a vibrating reed electrometer was used. The electrometer (E.T.I. model 330) is able to measure currents from 10^{-15} to 10^{-9} A. The chamber is connected to the head of electrometer through an anti-microphonic cable. With the anti-microphonic cable connected, the insulation of the collector was found to be better than 10^{14} Ohm. This

insulation is two orders of magnitude greater than the input resistors of the Vibron electrometer and consequently no current leakage is ~~detected~~ ^{considered}. The time constant is given by:

$$\tau = \frac{R_c \cdot R_1}{R_c + R_1} (C_c + C_1 + C_b)$$

where R_c is the collector insulation resistance, $> 10^{14} \Omega$,

R_1 is the input resistance of the electrometer,

C_c is the capacitance of the cable which is 67 pF
(1 m, 67 pF/m),

C_b is the chamber capacitance which is function of
the electrode spacings, i.e. 5 pF for 1 mm spacing,

C_1 is the input capacitance of the electrometer when
using the $10^{12} \Omega$ input resistors. With these
values the time constant becomes 1.5 min.

The following types of power supply have been used:

- a) a battery with a range of 30 to 1600 V,
- b) an "Oltronix" type high-stability power supply
(type LS 528) which gives HT up to 5000 V and
- c) a "Bradebourg" type power supply, which gives
HT up to 20.000 V.

A high-voltage condenser (4 x 2000 pF, 30 kV) was used for additional stabilization of the two latter HT sources. High purity normal hexane $[\text{CH}_3(\text{CH}_2)_4\text{CH}_3]$, manufactured by E. Merck, Darmstadt, was used. The conductivity of hexane is a function of many factors such as the applied field strength, the time after the electric field has been applied, the temperature of the liquid and, of course, the degree of purity of the hexane, etc. For the hexane used at 3000 V and 5 mm spacing, it was measured to be $10^{-18} \Omega^{-1} \text{cm}^{-1}$, which is slightly less than stated

by Adamczewski²³⁾ (10^{-19} to 10^{-20} cm^{-1} as corresponding to an upper limit of hexane purity).

C. MEASUREMENTS AND RESULTS

A series of measurements was made with the chamber, using γ -rays from a Ra^{226} source, 400 MeV neutrons, 600 MeV and 20 GeV/c protons from the CERN accelerators. The purpose of the γ ray, 400 MeV neutron and 600 MeV proton measurements was to find out the response of the chamber to the flux density (parameters being the HT) and to HT (parameters being the flux densities) for the mentioned radiations and also to study the statement of Blanc et al. on the possibility of measuring the LET with a liquid chamber. When using the 20 GeV/c protons (from slow ejection, an external proton beam of the PS accelerator) the response of the chamber to a pulsed proton beam was sought. The particular characteristics of each radiation source employed are described in the relevant chapter. The experimental results obtained are presented below. Some comments are also made concerning the residual current of the chamber.

1) The residual current

The residual current is the ionization current when the chamber, under HT, is exposed to background radiation only. The residual current is function of many parameters, as already mentioned in Chapter B. It is of considerable importance because it determines the lower limit of radiation intensity which a liquid chamber can detect and because, in the case of a liquid chamber, this is many times greater than the residual current of a gas-filled chamber of equivalent volume. Therefore, some of the results obtained on this current are given below:

- a) The time variation of the residual current is in general as shown in the curves of fig.2. The decrease of residual current with time can be explained supposing that an "electrolytic purification" of the liquid takes place^{1,23}). This is the reason why an electrolytic purification electrode was used in the present work. The high tension was first applied between this electrode and the anode, so that the liquid was purified electrolytically. During this operation, it is probable that the existing "impurities" are deposited on the opposite facing of these electrodes (see fig.1). The anode and collector surfaces thus remain clean. The high voltage was then applied between the anode and collector. In fig.2, some typical examples are given: curve (b) corresponds to a "virgin" liquid, i.e. before any electric field was applied; curve (a) corresponds to a normal process, i.e. the chamber was operated before with a lower field (3.500 V/cm), but without any tension on purification electrode; and curve (c) corresponds to the case where a strong field (50.000 V/cm) was applied between the purification electrode and anode before and during the experiment. The following can be concluded: In case (c), the "constant" value of the residual current is obtained in a shorter time than in cases (a) and (b), and the difference between this value and the initial value is smaller by a factor of 2 for the case (c), and by more than a factor of 3.5 for the other cases.

It was also observed that when the HT was switched off and on again, the ionization current came back to a level which depended on the time of application of the HT during the first stage, the time since the HT was turned off and the degree of agitation.

- b) The residual current density (A/cm^2) as a function of HT plotted on linear scales is shown in fig.3. Two parts can be distinguished on these curves; in the first part, for the low values of high tension, the current is nearly proportional to the applied voltage and the curve presents a small slope. For the second part, i.e. for higher HT values, it is difficult to establish a relationship between the current and the voltage where the slope of the curve is greater. The "sudden" changes of slope are functions of the electric field intensity, the spacing between the electrodes, the purity of the liquid and the temperature. In fig.4 the logarithm of the residual current density is plotted as a function of the HT on a linear scale, broken down into two straight lines. From the form of these curves the residual current density could be expressed as follows:

$$I_d = k \cdot e^{\alpha(HT)}$$

where the k and α values depend on the electrode spacing; the value of α for the upper part of the curves (fig.4) versus the electrode spacing is shown in fig.5. The slope of the dashed line is $= 0.375 \text{ Volt}^{-1} \text{ mm}^{-1}$.

- c) Some theoretical explanations have been proposed to give an understanding of the observed experimental results on residual current. The most important are:
- i) the phenomenon of cold electronic emission from the cathode (Schottky effect)³⁰⁻³²⁾
 - ii) the electrolytic dissociation of the hexane molecules and, in general, of dielectric liquids under the influence of strong electric fields³³⁻³⁵⁾ and
 - iii) the influence of "background radiation"³⁶⁾.

From experimental studies of the mechanism of conductivity of highly dielectric liquids it seems probable that this is ionic rather than electronic^{23, 37-39}). The mobility of ions was found to be relatively small and independent of the value of the applied electric field³⁹).

2) Gamma-ray experiments

The results of measurements with a Ra^{226} source of 50 ng which gives 16 rad/h at a distance of 5 cm can be summarized as follows:

- a) For the ionization current versus HT, two forms of the ionization curves are found which depend on the dose-rate (fig.6). One form corresponds to the lower dose-rate densities and is the same as the "typical" residual current curve - as in fig.3 - while for the higher dose-rates the ionization curves are straight lines, as shown in fig.6 for flux densities corresponding to 16 and 4 rad/h. Straight lines are also found if the "net" (by subtracting the residual current) ionization current is plotted, e.g. in the case of dose-rates 1 and 0.25 rad/h. The straight lines when extrapolated meet the HT axis at the same point. The phenomenon is also evident in the case of the straight lines found after subtraction of the background. These latter curves do not always give rise to straight lines, e.g. 0.01 rad/h. However, it is evident that for a given electrode spacing to obtain a linear function of the ionization current versus applied high voltage there must be a dose-rate higher than a threshold. From several observations of this linearity it can be concluded that the threshold moves towards higher flux values as the spacing decreases.

b) In plotting the net current versus distance between source and chamber, families of curves were obtained as shown in fig.7. The slope of the straight lines in the log-log plot is, in general ~ 2 . This means that the current is proportional to the dose-rate penetrating into the chamber. The parameters for these curves are the HT voltage. Here also we have two kinds of curves:

- i) curves for lower HT values which are entirely straight lines, and
- ii) curves for higher HT values which have a straight part corresponding to the higher dose-rates and a curved part corresponding to the lower dose-rates.

As the electrode spacing decreases the HT values at which the curves deviate from straight lines decrease also. The value of the threshold of this phenomenon is probably function of the electric field strength.

3. Experiments with neutrons

The chamber was exposed to high-energy neutron beams from the CERN SC accelerator. These beams are secondaries, scattering out at different angles (0° , 18° , 36° and 56°) from the 600 MeV synchro-cyclotron, using an internal Be target (4 cm). The measurements described below were made at 0° channel (at a tangent to the direction of the proton beam) outside the machine shielding and at 10 m from the target. ($\sim 1 \text{ g cm}^{-2}$ air depth). The Be target was placed at a radius where the energy of circulating protons was 400 MeV. The beam passed through air into the experimental hall where the charged particles were removed by a sweeping magnet. The energy spectrum of this neutron beam is shown in fig.8. This spectrum was measured at the same place where the liquid ionization

chamber was exposed, using the time of flight of proton recoil (elastic n-p reaction), diffused at given angles⁴⁰⁾. The characteristics of the beam used are given in Table I⁴¹⁾. The diameter of the beam was 26 cm. The beam intensity was found to be uniform within 10% over its area up to 1 cm from the edge of the profile.

Monitoring of the flux was made as follows: a Long Counter (LC) was placed 50 cm outside the beam axis; this was foreseen to follow the stability of the machine. A tissue-equivalent chamber (TE) was placed 10 cm behind the liquid chamber and both of them were at the centre of the beam. The absolute number of high-energy neutrons (>20 MeV) was found by a C^{11} activation measurement with carbon crystals [reaction $C^{12}(n,2n)C^{11}$]. Afterwards, the ionization current of the liquid chamber was related to the ionization current of the TE chamber.

The conversion factor for the TE chamber and the high-energy neutrons of this beam was found to be $1 \times 10^{-10} A$ to $1.7 n/cm^{-2}/sec.$ ⁴²⁾. The polarizing voltage of the TE chamber was 90V, far away from the threshold of saturation obtained with the maximum used flux density (see Baarli et al⁴²⁾); this means that the ionization current of the TE chamber could be considered to be proportional to the neutron flux density. The results of the experiments with neutrons are summarized in figs. 9 and 10.

a) In fig.9 the ionization current of the liquid chamber versus the current of the TE chamber (neutron flux) for various HT values of the liquid chamber and for electrode spacings of 5 mm is given. The linearity between ionization current of the liquid chamber and neutron flux density is shown. The straight lines when extrapolated meet the HT axis at the same point.

b) In fig.10 the ionization current versus HT is shown. The curves are given for 5 and 2.5 mm electrode spacings. The linearity of this function is good. As first observed by Blanc et al⁵⁾ the extrapolated straight lines for a same spacing but for different flux densities meet the HT axis at the same point. The flux density for the 5 and 2.5 mm spacings (expressed as the current of the monitor TE chamber) was $100 \times 10^{-12} \text{ A}$. As shown in fig.10, the "distance" of the "intersections" from zero are 4.4 and 2.3 kV which corresponds to 5 mm and 2.5 mm spacings respectively. If these distances are divided by the corresponding electrode spacings, the values found are approximately the same.

4. Experiments with protons

i) 600 MeV protons:

During the exposure of the chamber, the external proton beam of the SC accelerator was well known⁴²⁾. The absolute monitoring of flux density was performed by using a secondary emission chamber⁴³⁾, C^{11} activation [reaction $\text{C}^{12}(\text{p}, \text{pn})\text{C}^{11}$, threshold of reaction 20 MeV], and Na^{24} activation [reaction $\text{Al}^{27}(\text{p}, \text{pn})\text{Na}^{24}$, threshold of reaction 50 MeV]. For the relative monitoring of the liquid chamber, an air equivalent ionization chamber, filled with 1 atm. and of a volume of 0.6 cm^3 was used. In the following, this chamber will be called "Ionex"^{*)} chamber. In using the absolute monitoring systems referred to above, the conversion factor of the Ionex was $1.15 \times 10^{-19} \text{ A p}^{-1} \text{ cm}^2 \text{ sec}$. The Ionex chamber was placed on the beam axis, 1 cm in front of the liquid chamber. For full beam intensity the flux density in front of the liquid chamber was $\sim 10^9 \text{ p cm}^{-3} \text{ sec}^{-1}$; it is estimated that

*) Baldwin Ionex; Baldwin Instrument Co., Dartford, Kent., England.

this beam had in front of the chamber about 5% (to dose) neutrons and other particles. The results of these measurements are as follows:

The curve in fig.11 gives the ionization current against the current of the Ionex chamber. For high flux densities the ionization current seems not to be proportional to the flux density. If one assumes that the Ionex chamber current was proportional to the flux density (it was operated at a HT far above the shoulder on the saturation curve and its linearity was checked with activation method), then it can be deduced that the current in the liquid chamber deviates $\sim 50\%$ from linearity at $\sim 10^8 \text{ p cm}^{-2} \text{ sec}^{-1}$. For lower proton fluxes, (below $\sim 10^5 \text{ p cm}^{-2} \text{ sec}^{-1}$) it was found that the ionization current versus flux is straight lines.

The relation between ionization current and HT is shown in fig.12. Here also the curves are not straight lines in their overall length. It seems that the deviation from linearity is function of the flux density; for larger flux densities there are larger deviations, see e.g. curve a, fig.12. However, the curves - when extrapolated - meet the HT axis at the same point.

ii) 20 GeV/c protons:

The chamber was exposed to a high-energy external proton beam of the PS accelerator. The aim of this experiment was to study the response of the liquid ionization chamber to pulsed high-intensity proton beams. For this reason, the collector of the chamber was earthed with a 1 megohm resistance across which voltage pulses were measured. The pulses observed are shown in fig.13 (type A). To obtain the pulses, the oscilloscope was triggered by means of a pulse from a small plastic scintillator placed on the beam axis beyond the chamber and well shielded (1 m iron)

from the direct beam. The amplitude of these scintillation pulses (type B) has been used also as a relative monitor. As shown in fig.13, the two types of pulses have approximately the same form (rise time and pulse length). It was also found that the area under the pulse from the liquid chamber was proportional to the proton flux; further details of these experiments will be given in a separate publication⁴⁴⁾.

D. DISCUSSION

1) Gamma rays

In the γ -ray experiments it was found that the net ionization current I of the liquid ionization chamber (for fixed chamber conditions, i.e. electrode spacing and HT) was proportional to the γ -ray flux density incident in the chamber (fig.7). However, for small γ -ray flux densities there is a deviation from linearity. The "threshold" for this deviation is function of the HT value and of the electrode spacing. For a fixed electrode spacing, the linearity between ionization current and flux density improves with decreasing HT values.

These remarks apply also for the variation of the ionization current with HT. For higher flux density values, beyond a certain value of HT, there is a linear relation between ionization current, I , and HT. In general, the threshold of flux density, to obtain linear relation of ionization current versus HT, is function of the electrode spacing.

The linear portions of the ionization curves may be expressed in the form:

$$I = a(HT) + b \quad (1)$$

(Jaffé's formula) where a and b are the parameters which generally depend upon many factors (e.g. electrode spacing, temperature, etc.). However, under carefully controlled conditions, a and b are function of the type of radiation employed only. As noted by Blanc et al.⁵⁻⁷⁾ and later confirmed by Ladu et al.⁸⁾, the linear relation between ionization current and HT when extrapolated, meets the HT axis at a fixed intercept which is independent of γ -ray flux density. For the same type of radiation and for fixed radiation intensity a and b are constant.

The present work confirms this relation in the case where the flux is greater than a certain threshold value. This threshold in turn depends on the chamber parameters, such as the electrodes, electric field, purity of liquids, etc. From equation (1) this voltage intercept is given by $V_Y = -\frac{a}{b}$, and if we want this point to be fixed the ratio $\frac{b}{a}$ must be constant. Thus, though a and b vary with the change of γ -ray flux density, their ratio does not change. Values of $\frac{a}{b}$ for various electrode spacings are given in Table II. In column 3 of this table the ratios $\frac{b}{a}$ divided by the respective electrode spacings are given. As can be seen,

$$(V_Y^* = \frac{b}{a \cdot d}, \text{ where } d \text{ is the spacing})$$

increases slightly as the electrode spacing decreases. However, the increase of V_Y^* could be due to the uncertainty in the determination of smaller electrode spacings. For an electrode spacing of about 5 mm the average value of V_Y^* was estimated to be 1.2 kV/mm.

From the data of Blanc et al.⁷⁾, the voltage intercept for γ -rays corresponds to 5.2 kV which gives 1.7 kV/mm for the 3 mm spacing. The difference between the V_Y^* value found by Blanc et al. and the one found in the present work could be attributed to the purity of the hexane used; the hexane used by Blanc et al. was of higher purity.

The hypothesis that the difference in the V_{γ}^* values is due to the difference in energy of the γ -rays used (Blanc et al. used Co^{60} , while in the present study Ra^{226} was used), cannot be shared as there is almost no difference between the quality factor of these two radiation sources. The relation between V_{γ}^* and QF is discussed later in the text.

2) Neutrons

The results discussed above for the γ -ray irradiation of the chamber apply also for the case of neutron irradiation. A summary of these results would be:

- i) the ionization current is proportional to the neutron flux density
- ii) there is a linear relation between ionization current and HEP
- iii) the V_n^* values (where V^* has the same meaning as for the γ -rays) for 5 and 2.5 mm electrode spacings were found to be of 0.9 kV/mm and 1.0 kV/mm respectively.

The difference between these two V_n^* values is not big but, as it was found for the γ -radiation, V_n^* increases as the electrode spacing decreases.

3) Protons

The measurements with high-energy protons showed that when the flux was very high (10^8 p cm⁻² sec⁻¹) there was no linear relation between ionization current and flux density. However, if the flux is lower by a factor of $\sim 10^3$, the linearity between these two parameters exists. The relation between ionization current and HT is given in fig.12. Here, also, there is a deviation from the linearity. This lack of linearity is more pronounced for a larger flux density (curve a, fig.12) than for a smaller flux density (curve b, fig.12). The linear parts of the ionization currents versus HT, when extrapolated back, meet the HT axis at the same point. The V_p^* value from these measurements was found to be of 1.14 kV/mm, for 5 mm spacing.

4) Quality Factor

Blanc et al.⁵⁻⁷⁾ have proposed that the co-ordinate of the intersection points on the HT axis be related to the QF of the radiation considered. This hypothesis, if valid, is of great interest as it would then be possible to estimate the QF of an unknown mixed radiation field by using a calibrated liquid ionization chamber. The results obtained in the present work confirm the above proposal of Blanc et al. The quality factor for "400" MeV neutron and 600 MeV proton beams were measured by Baarli et al.^{41,45)}. In fig.14 we give the relation between QF and V^* . It appears that there is a function between QF and V^* . One of the more important requirements would be to find out an analytical expression for this curve. It should be possible to determine this relation by simultaneous exposures of the liquid ionization chamber and the Sullivan-Baarli parallel plate high-pressure ionization chamber and also the Rossi LET chamber.

E. CONCLUSIONS

The study of liquid ionization chambers is interesting from two points of view:

- a) pure physics as far as the conductivity mechanism of dielectric liquids is concerned
- b) dosimetry. For dosimetry, a liquid chamber presents some advantages, e.g. the density and composition of the liquid ionized is similar to that of soft tissue; but the chamber presents also some disadvantages, e.g. lower sensitivity as compared to a gas ionization chamber.

The aim of a more thorough study of the liquid ionization chamber would be to point out the relation between the QF or LET of a given radiation and the response of the chamber. The present work demonstrates a part of this property and confirms the fact that the ionization curves for the gamma radiation intersect the HT axis at the same point. This phenomenon was observed for high-energy protons and neutrons and the intercepts are well separated from each other for the chamber used and the radiation employed. The results are shown in fig.14.

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FIGURE CAPTIONS

- 1) Design of the liquid chamber.
- 2) Time variation of residual current. For curves α and b, no electric field was applied between anode and purification electrode (curve b corresponds to "virgin" liquid). For curve c the extra electrode was used.
- 3) Residual current against HT, plotted lin-lin. Electrode spacing: 1.25, 2.5 and 5 mm.
- 4) Residual current against HT, plotted log-lin.
- 5) Function of α (see text, formula $I_d = k e^{\alpha(HT)}$) against electrode spacings.
- 6) Net ionization current (ionization current out of residual current) versus HT. Source: 50 mg Ra^{226} ; spacing: 5.0 mm. Parameter flux of γ rays.
- 7) Net ionization current (ionization current out of residual current) versus distance source-chamber. Source: 50 mg Ra^{226} ; spacing: 5.0 mm. Parameter the HT.
- 8) Energy distribution of neutron beam used.
- 9) Ionization current of liquid chamber versus current of TE chamber for the case of "400" MeV neutrons. Spacing: 5,0 mm, parameters HT. The current of TE chamber was checked to be proportional to neutron flux density.
- 10) Ionization current versus HT for the case of "400" MeV neutrons; spacing: 2.5 and 5.0 mm; parameter: neutron flux density. (Curve α corresponds to $100 \cdot 10^{-12} A$, b corresponds to $65 \cdot 10^{-12} A$, c corresponds to $50 \cdot 10^{-12} A$ and d corresponds to $25 \cdot 10^{-12} A$ current of TE chamber).

- 11) Ionization current of liquid chamber against current of Ionex chamber for the case of 600 MeV protons. The current of the Ionex chamber was found to be proportional to the proton flux density. Spacing: 5.0 mm.
- 12) Ionization current versus HT for the case of 600 MeV protons. Spacing: 5.0 mm. The current of curve α must be multiplied by a factor 100. Curve a corresponds to $1.25 \cdot 10^7 \text{ p cm}^{-2} \text{ sec}^{-1}$, curve b corresponds to $1.50 \cdot 10^5 \text{ p cm}^{-2} \text{ sec}^{-1}$.
- 13) Pulse A, from an external high-energy proton beam of PS, obtained with the liquid chamber. Pulse B was obtained at the same time with a plastic scintillator.
- 14) The QF and V^* relation for the liquid ionization chamber used.

TABLES

Table I : Properties of the neutron beam.

Table II: V^* and spacings for the γ radiation.

Table I

Beam channel MeV	Target position	Proton energy	Channel angle	Max. neutron energy $E_n = E_p \cos \phi$	Total dose	Neutron dose	Gamma dose	C^{11} neutron flux
		MeV		MeV	rad/h	rad/h	rad/h	n/cm ² /sec
80	71° 176 cm	400	0°	400	3.03	3.03	0.37	$2.15 \cdot 10^5$

Table II

Electrode spacing d mm	$V_{\gamma} = \frac{b}{a}$ kV/mm	$V_{\gamma}^* = \frac{b}{ad}$ kV/mm
7.5	9	1.2
5.0	5.9	1.18
2.5	2.9	1.16
1.25	1.57	1.26
0.62	0.81	1.30
0.31	0.49	1.55