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*SURVEY ARTICLE*

# ON DIFFUSION CLOUD CHAMBERS

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A short survey is given on the development of the diffusion cloud chamber. Langdorf's theory is briefly reproduced, and some important improvements in the theory made by Shutt and other investigators are mentioned. Different diffusion cloud chambers are described, and photographs of tracks demonstrate the use of these chambers.

## 1. Introduction

In spite of the important results obtained with the wellknown Wilson-chamber the equipment has the great disadvantage of being able to record tracks of charged nuclear particles only in a time interval which is short (at the best 10 percent) compared with the time necessary for making the chamber ready for a new record. This disadvantage was partly removed, in any case for cosmic rays, when it was possible to let the particles themselves release the operations necessary for a photographic record of the events, which had occurred in the chamber1, 2, 3, 4). Later, the high energy accelerators were able to produce such a large yield of mesons that the need for a cloud chamber sensitive at any instant was obvious. However, the desire to make such an apparatus was of current interest long before the cosmotrons appeared.

In order to make a continuously working cloud chamber, one has either to find a new principle for the recording of tracks of charged particles, or still to use supersaturated vapours, but these should be produced continuously instead of being created in adiabatic expansions.

The first way was tried by Regener5), who used a cloud of small slowly-falling oil droplets. An ionizing particle going through this cloud made the oil droplets along the path of the particle electrically charged. A moment later the cloud passed through an electric field between two condenser plates. In this field the charged oil droplets were separated from the uncharged droplets. By use of an illumination equiment it was then possible to observe and to take photographs of the charged droplets, which formed the tracks to be studied. The quality of the tracks was, however, not good.

On the other hand the second method, the continuous production of supersaturated vapours, has given extraordinarily good results. The first experiment was made by Hoxton6), who let air pass over hot water and then through an observation channel at room temperature. However, Hoxton got condensation phenomena only by means of electric discharges. Paths of particles were not obtained.

Vollrath7) used vapours of HCl and water, which diffused through each other. The vapour mixture was then supersaturated with respect to both components. Paths of charged particles were observed in the supersaturated region. A disturbing effect was turbulences in the neighbourhood of the tracks. These whirls were caused by heat liberated in the condensation process. The cloud chamber principle of Vollrath was therefore not able to compete with that of

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1) D. Skobelzyn, Z. Phys. **54** (1929) 686.

2) L. M. Mott-Smith and G. L. Locher, Phys. Rev. **38** (1931) 1399.

3) Th. H. Johnson, W. Fleisher, Jr. and J. C. Street, Phys. Rev. **40** (1932) 1048.

4) P. M. S. Blackett and G. Occhialini, Nature **130** (1932) 363.

5) E. Regener, Festschrift der Technischen Hochschule Stuttgart (1829–1929) p. 331.

6) L. G. Hoxton, Proc. Virginia Acad. Sci., Abst. **9** (1933–34) 23.

7) R. E. Vollrath, Rev. Sci. Inst. **7** (1936) 409.

Langsdorf[8]). Langsdorf's principle has been the basis for all later constructions of continuously working cloud chambers. A more detailed account of the contribution by Langsdorf might therefore be justified.

## 2. The Diffusion Cloud Chamber by Langsdorf

Langsdorf[8]) made his diffusion cloud chamber at M.I.F. already 20 years ago. A vapour, usually methanol, diffuses vertically downward through a permanent gas (carbon dioxide or air) from the upper, heated part of the cloud chamber to the bottom plate, which is effectively cooled by means of, for instance, carbonic acid ice. The vapour is condensed on the bottom. plate. In an intermediate region supersaturation will occur to such an extent, that tracks of ionizing particles appear.

The construction of the cloud chamber is shown schematically in fig. 1. Methyl alcohol is heated in the boiler F by means of the radiant heater G. The vapour developed is distributed in the space A and flows through the holes K into the cloud chamber B. K is heated by means of the electric heaters M. The floor of the cloud chamber is made of two glass sheets C, between which a cooling liquid is pumped by a pump E. The liquid is cooled in the coil H by carbonic acide ice (the return tube is not shown). The tracks of ionizing particles are photographed from below by means of the camera R. The gas pressure in the chamber is kept near 1 atm by the gas float reservoir N. The sensitive region was about one inch deep near the chamber floor. Later it was possible to increase this region to 3–4-inches. When the sensitive layer is thick, however, the tracks are not as sharp as for thinner sensitive regions. An electric field (100 V/cm) is applied either between different parts of a system of grid wires or between the plate K and the bottom of the chamber. In this way most of the ions formed in the upper, insensitive region of the chamber are removed. Otherwise these ions, when entering the sensitive region, would cause a disturbing condensation.

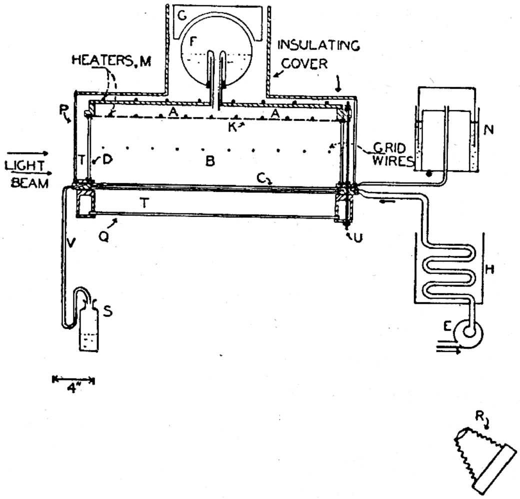

Fig. 1. Schematic drawing of Langsdorf's diffusion cloud chamber (Rev. Sci. Inst. **10** (1938) 91).

## 3. Langsdorf's Theory for the Diffusion Cloud Chamber

Langsdorf made some calculations under simplified assumptions. Thus, the influence of the walls of the cloud chamber is neglected in order to get one-dimensional equations for the diffusion and heat transfer. The formation of droplets is also neglected, and the vapour is treated as a perfect gas even when supersaturated. The vapour and heat fluxes are considered stationary.

### 3.1. TEMPERATURE DISTRIBUTION IN THE DIFFUSION CLOUD CHAMBER

If the height over the bottom plate be $x$, the energy flux $f$ through the chamber in cal$\cdot$cm$^{-2}\cdot$sec$^{-1}$ is

$$f = c_1 C_p t - K_0(1 + bt)\frac{dt}{dx} \;. \tag{1}$$

The first term on the right hand side of (1) is the heat transported by the mass flux $c_1$, the second term represents the heat conduction. The symbols in (1) are defined by

$c_1$ = flux of vapour in g$\cdot$cm$^{-2}\cdot$sec$^{-1}$
$C_p$ = specific heat of vapour in cal/g/degree
$t$ = temperature $T$ at $x$ minus temperature $T_0$ of the bottom plate
$K_0$ = heat conductivity of mixture at $T_0$
$b$ = temperature coefficient of heat conductivity $K = K_0(1 + bt)$.

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[8]) A. Langsdorf, Jr., Phys. Rev. **49** (1936) 422; **51** (1937) 1026; Rev. Sci. Inst. **10** (1938) 91.

Introducing the parameter $r$, defined by

$$f = c_1 C_p t_1 r \tag{2}$$

into (1), integrating and using the boundary conditions $x = 0$, $t = 0$ and $x = h$, $t = t_1$, where $h$ is the height of the chamber, one gets

$$x = \frac{K_0}{c_1 C_p}\left[bt + (1 + brt_1)\log\left(1 - \frac{t}{rt_1}\right)\right] \tag{3}$$

and hence

$$h = \frac{K_0}{c_1 C_p}\left[bt + (1 + brt_1)\log\left(1 - \frac{1}{r}\right)\right] \cdot \tag{4}$$

These relations give the temperature distribution in the cloud chamber. Fig. 2 shows some of the distributions computed by Langsdorf for three different values of the vapour flux $c_1$.

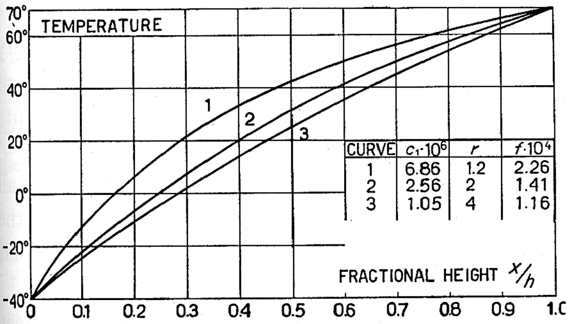

Fig. 2. Temperature distribution for different vapour fluxes according to Langsdorf (Rev. Sci. Inst. **10** (1938) 91).

## 3.2. DISTRIBUTION OF VAPOUR PRESSURE IN THE DIFFUSION CLOUD CHAMBER

The next step in Langsdorf's theory comprises the calculation of the vapour pressure as a function of $x/h$. For one-dimensional isothermal diffusion Salin[9]) gives the equations

$$\begin{cases} C_1 = wD_1 - k\,\dfrac{\partial D_1}{\partial x} \\ C_2 = wD_2 - k\,\dfrac{\partial D_2}{\partial x} \\ w \;= c_1 v_1 - C_2 v_2 \end{cases} \tag{5}$$

We have

$C_1$ = flux of vapour in $\mathrm{g \cdot cm^{-2} \cdot sec^{-1}}$
$C_2$ = flux of gas, in this case = 0
$D_1$ = concentration of vapor = $M_1 p_1/RT$
$D_2$ = concentration of gas = $M_2 p_2/RT$
$M_1$ = molecular weight of vapour
$M_2$ = molecular weight of gas
$p_1$ = pressure of vapour
$p_2$ = pressure of gas
$w$ = convective flux associated with diffusion
$k$ = diffusion constant = $(K_0/P_0)/(T/T_0)^{1+\alpha}$
$\alpha$ = temperature coefficient
$P_0$ = total pressure in chamber in atm
$T_0$ = 233°K = temperature of surface bottom layer.

Considering $c_2 = 0$ and the expressions for $D_1$, $D_2$ and $k$ the equations (5) give

$$\frac{\mathrm{d}p_2}{p_2} = \frac{c_1 R T_0 \mathrm{d}x}{M_1 k_0 \left(1 + \dfrac{t}{T_0}\right)^{\alpha}} \cdot \tag{6}$$

For methanol and carbon dioxide $\alpha \approx 1$. If d$x$ is expressed in terms of d$t$ by means of (1) and $\alpha = 1$, integration of (6) gives

$$\frac{\log p_2(t)}{\log p_2(0)} = \frac{T_0}{T_0 + rt_1} \cdot \frac{RT_0 K_0}{M_1 k_0 C_p}\left[(1 + brt_1)\log\left(1 - \frac{t}{rt_1}\right) - (1 - bT_0)\log\left(1 + \frac{t}{T_0}\right)\right] \cdot \tag{7}$$

This equation gives the relation between the pressure of the gas (and hence also immediately that of the vapour) and the temperature. In connection with (3),(4) or fig. 2, we then get the connection between $p_1$, $p_2$ and $x/h$. Fig. 3 shows the pressures which correspond to the curves in fig. 2.

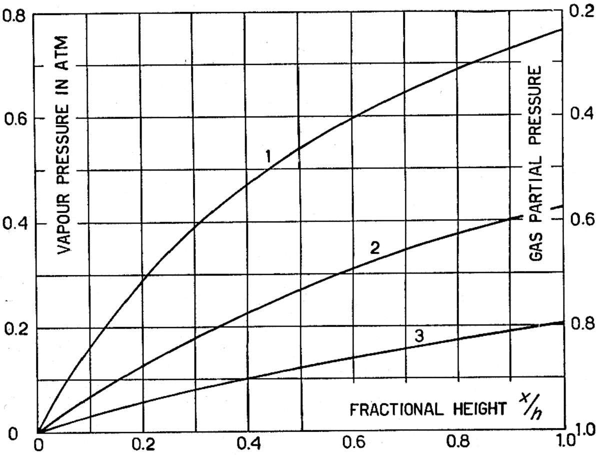

Fig. 3. Vapour pressure distribution for the vapour fluxes given in fig. 2, according to Langsdorf (Rev. Sci. Inst. **10** (1938) 91).

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[9]) J. Kuusinen (now Salin), Ann. d. Physik **24** (1935) 445, 447.

### 3.3. CALCULATION OF THE SUPERSATURATION

Using (6), the supersaturation $S$ may be determined by

$$\begin{aligned} S &= p_1/p_{1S} = (P_0 - p_2)/p_{1S} \\ &= [P_0 - p_2/p_2(0)\,(P_0 - p_1(0))]/p_{1S} \\ &\approx P_0\,(1 - p_2(t)/p_2(0))/p_{1S} \quad . \end{aligned} \tag{8}$$

Consequently, the supersaturation will be nearly proportional to the total pressure.

Because $x$ does not appear in (7) and only as $x/h$ in (3):(4) it is seen that if $r$ is kept constant, also the form of the supersaturation curve is unaltered. However, $c_1$ decreases when $h$ increases (see 4)), and the lower vapour flux might be unsufficient for a satisfactory operation of the diffusion chamber, because the higher the chamber, the more vapour is spent to form droplets by condensation. Therefore, the diffusion cloud chamber should not be made too high.

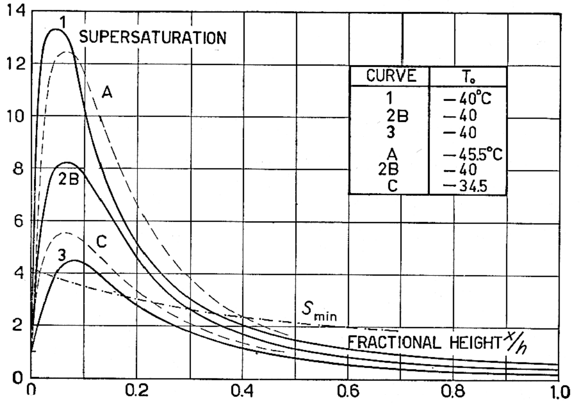

Fig. 4. Supersaturation distribution (the curves 1, 2B, 3) for the three vapour fluxes given in fig. 2, and supersaturation distribution (the curves A, 2B, C) for different bottom temperatures according to Langsdorf (Rev. Sci. Inst. **10** (1938) 91).

The curves 1, 2B, 3 in fig. 4 show the distribution of the supersaturation for the three vapour flux values 1, 2, 3 given in fig. 2. For these three curves $T_0 = -40°$C. The dot-dashed curve $S_{\min}$ shows a rough estimate of the minimum saturation, which is necessary for condensation upon ions,

$$\log S_{\min} = A \cdot \frac{M}{d} \cdot \frac{\sigma^{4/3}}{T}\,, \tag{9}$$

which corresponds to calculations made by Powell[10]). $A$ is a constant, $M$, $d$, and $\sigma$ are the molecular weight, density and surface tension, respectively, of methanol, and $T$ the absolute temperature. That part of the fractional height $x/h$, which is defined by the points of intersection between $S_{\min}$ and some of the supersaturation curves, corresponds to the sensitive region of the cloud chamber. The curves 1, 2B, 3 show that the sensitive region becomes higher when the vapour flux increases. The curves A, 2B and C belong to the same flux $c_1 = 2.56 \times 10^{-4}$g/cm² sec and show the influence of $T_0$ on the supersaturation. Thus a lower $T_0$ increases the height of the sensitive region.

## 4. Further Contributions to the Diffusion Cloud Chamber Theory

Shutt[11]) at Brookhaven National Laboratory has made a more strict analysis of the conditions in the diffusion cloud chamber by taking into account the following circumstances:

(1) A one-dimensional diffusion equation shall relate the downward flux of vapour to the vapour density at all points except near liquid drops.

(2) Spherically symmetrical vapour and heat diffusion equations determine the growth of the drops.

(3) Stoke's equations determines the rate of fall of the drops through the regions at varying temperatures.

(4) A relation is set up between the gradient of the vapour flux and the rate at which vapour is removed by condensation of drops on ions.

(5) An energy equation shall make it possible to calculate the convection in the gas necessary to establish proper heat exchange with the walls.

Shutt found that the temperature gradient as a function of $x$ depends with good approximation only on the single parameter $\beta$:

$$\beta_a = \mu_0 P^{5/3} (n_0 \tau Z)^{4/3} k_0^{-\frac{1}{3}} \quad \text{if} \quad T < 260°\ \text{K} \tag{10a}$$

$$\beta_b = \mu_0 P^2 (n_0 \tau Z)^{4/3} k_0^{1/3} \quad \text{if} \quad T > 260°\ \text{K}\ . \tag{10b}$$

The notations, meanings and values of the quantities in the expressions for $\beta$ are given in table 1.

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[10]) C. F. Powell, Proc. Roy. Soc. **119** (1928) 553.

[11]) R. P. Shutt, Rev. Sci. Inst. **22** (1951) 730.

TABLE 1

DATA FOR CALCULATION OF THE PARAMETERS $\beta$ FOR AIR (SHUTT[11]))

| Symbol | Explanation | Value |
|---|---|---|
| $Z$ | Atomic number for the gas | 7. 2 |
| $\tau$ | Number of atoms in gas molecule | 2 |
| $k_0$ | Diffusion constant at N.T.P. | 0.133 |
| $K_0$ | Heat conductivity at N.T.P. | $5.3 \times 10^{-5}$ |
| $\mu_0$ | Viscosity of gas-vapour mixture at N.T.P. | $1.71 \times 10^{-4}$ |
| $P$ | Total pressure in atm | 1 |
| $n_0$ | Number of ions per cm³ per sec at N.T.P., liberated by the radiation considered. For cosmic radiation $n_0 =$ | 2 |

For air at N.T.P. $\beta_a = 0.77 \times 10^{-2}$, $\beta_b = 1.47 \times 10^{-4}$. Fig. 5 shows some temperature distributions calculated by Shutt for different parameters, temperatures and temperature gradients at the bottom of the diffusion cloud chamber. The distributions have a form different from those calculated by Langsdorf (fig. 2). Fig. 6 shows the experimentally found temperature distribution in a diffusion cloud chamber made by the author (similar temperature distributions have been published by Morrison and Plain[12]). It is obvious that this type of temperature distribution is in closer agreement with the form given by Shutt than by Langsdorf.

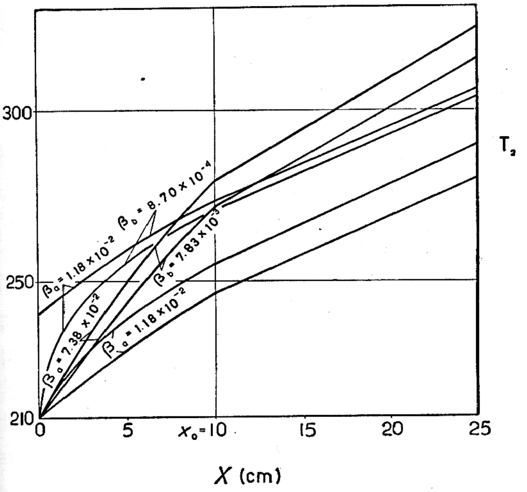

Fig. 5. Temperature distributions for different parameters, and for different temperatures and temperature gradients at the bottom of a diffusion chamber, according to Shutt (Rev. Sci. Inst. 22 (1951) 730).

The parameters[10]) are of great interest. One finds, for instance, that different gases might give identical temperature distributions, if the pressures are chosen in a suitable way. Thus, table 2 shows the relative pressures computed from[10]) for a number of gases under the conditions that the temperature distributions be the same as for air.

TABLE 2

$P/P_{air}$ = PRESSURES OF SEVERAL GASES, RELATIVE TO AIR, REQUIRING IDENTICAL TEMPERATURE DISTRIBUTIONS (SHUTT[11]))

| Formula | $H_2$ | $D_2$ | He | A |
|---|---|---|---|---|
| 10 a | 9.7 | 7.7 | 5.6 | 0.70 |
| 10 b | 6.1 | 4.5 | 3.7 | 0.75 |

The formulas (10) show further, that an increase of the ionization density by a certain factor has the same effect as if $P$ is increased by the same factor raised to the $^4/_5$ power (10a) or to the $^2/_3$ (10b). Hence, if $n_0$ becomes so large that the diffusion cloud chamber stops functioning a reduction of the pressure might possible bring the apparatus to operate again.

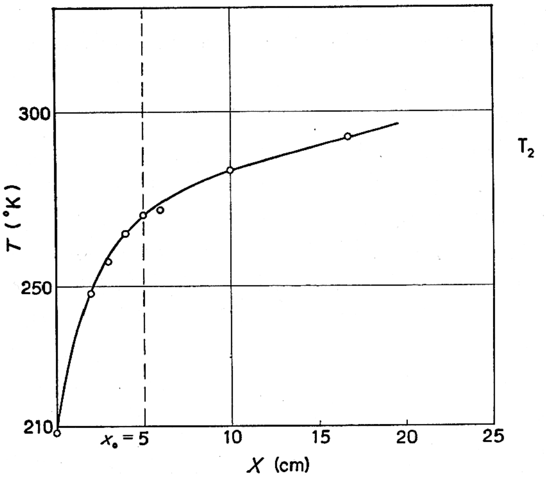

Fig. 6. Experimental temperature distribution in an 1 atm air-methanol diffusion cloud chamber. Depth of sensitive layer 2 in. (Slätis[36, 37])).

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[12]) H. L. Morrison and G. J. Plain, Rev. Sci. Inst. 23 (1952) 607.

Succi and Tagliaferri[13]) in Milano have considered the influence of ionization in a simpler way than Shutt did. The radii of the droplets are supposed to grow as the square root of the time, and the droplets are assumed to fall with constant velocity. The effect of release of heat of condensation is considered. Advice concerning the choice of chamber gas and vapour is given.

Bevan[14]) (Harwell) applied Shutt's strict theory studying the optimum conditions for diffusion chambers[15]). The theory was completed by taking account of the formation of neutral condensation nuclei and thus the parameter $\beta_a$ (10) was a little modified, and called $B_a$. Bevan gives in diagrams the connection between $B_a$ and minimum temperature gradient, position and temperature of the alcohol trough in order to get tracks at —20° C, as well as that trough temperature, above which distrubances in the normal operation of the diffusion cloud chamber appear.

## 5. Examples of some Diffusion Cloud Chambers

The Langsdorf[8]) diffusion cloud chamber, already described, was not very simple, and the charged particle tracks published were not of the same quality as tracks obtained in the Wilson-chamber. This explains the long time-lag before the diffusion cloud chamber aroused more intense interest. Not until Needels and Nielsen[16]), and—may be still more—Cowan[17]) had shown how it was possible—using very simple constructions—to get tracks as good or still better than those obtained in the Wilsonchamber, did the construction of diffusion cloud chambers start. Cloud chambers were made for demonstration purposes as well as for recording nuclear particles created in experiments with high energy accelerators.

Needels and Nielsen[16, 18]) (Ohio State University) simply put a glass beaker on a block of dry ice and covered it with a sheet of cardboard moistened with alcohol. Ion tracks of excellent quality and sharp tracks of both electrons and protons were observed in a shallow layer near the cold bottom of the beaker. The best working conditions were obtained when a clearing field was placed across the sensitive region. In order to have better vision from above, a hole was cut in the cardboard and covered with a glass plate, and a piece of black velvet cloth moistened with alcohol was put in the bottom of the beaker. The height of the sensitive region could be increased by use of mixtures of different alcohols and water.

Choyke and Nielsen[19]) made a low pressure (75–15 cm Hg) diffusion chamber filled with helium and ethanol. The bottom plate was cooled to approximately —130° C by inserting an aluminium cylinder connected to the bottom plate into a Dewar flask filled with liquid nitrogen. The maximum permissible top temperature for a helium filled chamber was calculated to be and kept at —20° C.

Cowan's[17]) diffusion cloud chambers are similar to those of Needels and Nielsen. Fig. 7 shows one of the cloud chambers schematically.

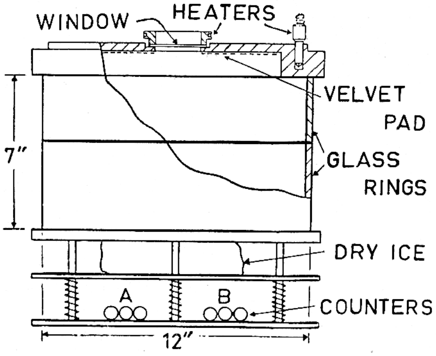

Fig. 7. Schematic drawing of Cowan's diffusion cloud chamber (Rev. Sci. Inst. **21** (1950) 991).

This type can be considered as a pattern for all later diffusion cloud chambers. The floor of the chamber is made of aluminium blackened by an anodizing process or of black bakelite. This bottom is cooled by direct contact with a block

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[13]) C. Succi and G. Tagliaferri, Nuovo Cimento **9** (1952) 1092.

[14]) A. R. Bevan, A.E.R.E. GP/R (1953) 1215.

[15]) M. Snowden and A. R. Bevan, J. Sci. Inst. **30** (1953) 3.

[16]) T. S. Needels and C. E. Nielsen, Rev. Sci. Inst. **21** (1950) 976.

[17]) E. W. Cowan, Rev. Sci. Inst. **21** (1950) 991.

[18]) C. E. Nielsen, T. S. Needels and O. H. Weddle, Rev. Sci. Inst. **22** (1951) 673.

[19]) W. J. Choyke and C. E. Nielsen, Rev. Sci. Inst. **23** (1952) 307.

of dry ice. The cylindrical glass wall is made of two glass rings, separated by a conducting rubber gasker which is one of the sweep-field electrodes. The other electrode is the top and bottom of the chamber. This arrangement removes the ions from the upper part of the chamber without pulling them down into the sensitive layer. The top plate of aluminium is heated electrically and carries a velvet pad sewn to a perforated aluminium sheet. A glass window in the centre of the top makes it possible to take photographs of the tracks in the chamber. The exposure may be released by the G.M.-counters below the bottom of the chamber, for instance, in the case of cosmic rays by mesons.

The height of the sensitive layer is about 3 inches at a top temperature of 44° C, if the chamber is filled with air and methanol. With a liquid mixture of about equal parts of methyl alcohol, ethyl alcohol, and water, it is possible to obtain a sensitive layer five or six inches deep after passing a pulse of sweep voltage.

When photographed, the tracks are illuminated by means of a flash lamp (General Electric Type FT-422), connected to 250 $\mu$F charged to a voltage of 2000 volts. When operated with counter control, a sweep voltage pulse of 1.5 sec duration and 600 volts amplitude is applied every 45 seconds.

The first high pressure diffusion cloud chamber was constructed by Miller, Fowler, and Shutt[21]). Experiments were made with methanol and hydrogen (12–16.5 atm), helium (3.1–8.9 atm) and air (1–3.1 atm). With $H_2$ or He, violent conversion occurs up to a pressure at which the density gradient from top to bottom becomes positive. At 12 atm the hydrogen-filled cloud chamber records continuously ionizing radiation having an intensity 2–3 times that of cosmic rays at sea level. On the other hand, there is no limit to the chamber's ability to record bursts of radiation if an electric sweeping field is applied during the intervals. A novelty was the temperature distribution control along the stainless steel walls by means of heating wires soldered to them.

Immediately after this Shutt, Fowler, Miller, Thorndike, and Fowler[22]) made a new high pressure diffusion cloud chamber for 21 atm working with hydrogen and methanol vapour filling. The bottom temperature was —65° C and the top temperature +20° C. The chamber was used for a study of the scattering of the 60 MeV $\pi^-$-mesons from the Columbia University Nevis cyclotron. After some changes, the construction[23]) of the cloud chamber was that shown schematically in fig. 8. To the left a vertical projection, to the right a horisontal projection of the chamber is seen. It consists of welded steel bottom and top cylinders separated by a bakelite insulating ring (5). The bottom can has a $^1/_4$-inch stainless steel cylinder wall (1) and a 1.25-in. bottom plate (2), and top flange (3). The top is made in a hat shape so that the top window (6) can be close to the camera and hence be small in size. The copper through (9) is in good thermal contact with the base plate (10) of the top. Cooling coils (13) at the bottom and heating wires at the top (14) and the side (15) provide temperature control of the chamber, which is temperature insulated (16) from the surrounding air. The tracks are illuminated through windows

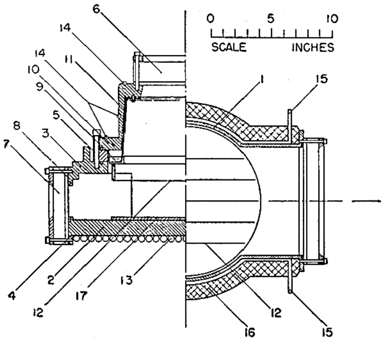

Fig. 8. Diagram of diffusion chloud chamber designed for operation at 20 atm according to Fowler, Fowler, Shutt, Thorndike, and Whittemore (Phys. Rev. **91** (1953) 135).

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[20]) M. M. Block, W. W. Brown and G. G. Slaughter, Phys. Rev. **86** (1952) 583.

[21]) D. H. Miller, E. C. Fowler and R. P. Shutt, Rev. Sci. Inst. **22** (1951) 280.

[22]) R. P. Shutt, E. C. Fowler, D. H. Miller, A. M. Thorndike and W. B. Fowler, Phys. Rev. **84** (1951) 1247.

[23]) E. C. Fowler, W. B. Fowler, R. P. Shutt, A. M. Thorndike and W. L. Whittemore, Phys. Rev. **91** (1953) 135.

(7) by light from flash tubes. A sweeping field is obtained by a suitable voltage on the wires (12).

The good results obtained with this diffusion cloud chamber gave rise to the construction of still larger chambers for the Cosmotron at Brookhaven National Laboratory. Thus a larger chamber[24]) of a type similar to that already described was built, having a diameter of 16 inches and operating in a field of 10 500 oersted.

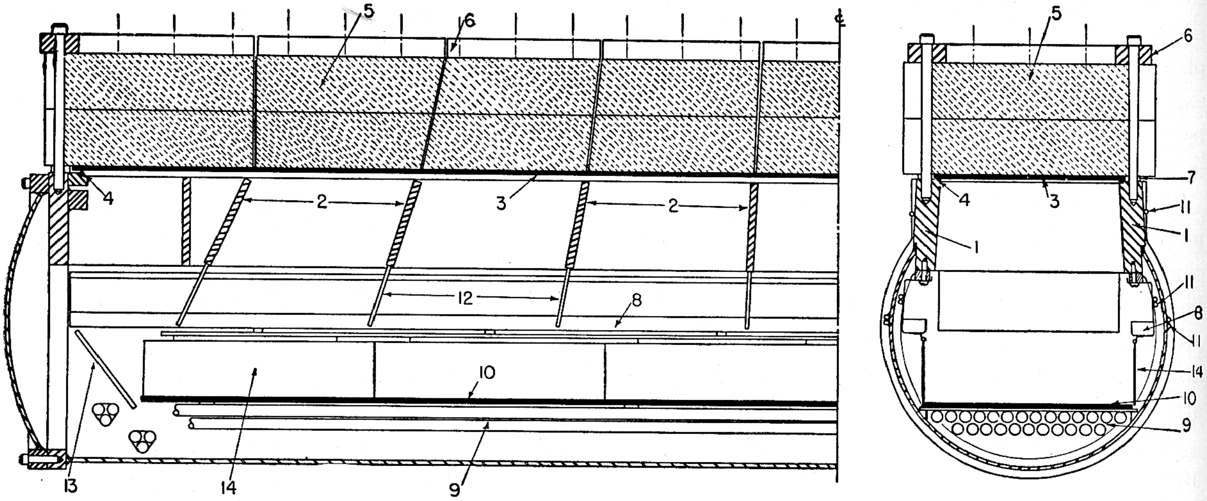

Fig. 9. Schematic drawing of the 6 foot diffusion cloud chamber at Brookhaven. The chamber operates with $H_2$ or He at pressures up to 21 atm and is used in connexion with the Cosmotron. At the right a transverse section through the centre is shown. At the left, one half of a lengthwise section is given, the other half being symmetrical. Fowler, Shutt, Thorndike, and Whittemore (Rev. Sci. Inst. 25 (1954) 996).

In order to be able to record more events, a long cloud chamber with an effective length of 6 ft, width of 11 in., and no magnetic field was built. Fig. 9 shows this chamber schematically. It has a horizontal cylindrical shape, but with the top of the cylinder modified to provide a window, consisting of a single Allite sheet $^1/_4$in. thick (3) and heavy Lucite blocks (5). The window is mounted on heavy longitudinal bars (1) with transverse tie bars (2). The bottom is cooled by a set of cooling coils, through which trichloroethylene is pumped at the temperature of dry ice. Vapour is supplied to the chamber from methyl alcohol in trays (8) thermally insulated from and mounted on the side bars. The temperature distribution is controlled by heating wires through copper tubes (11) soldered to the sides of the chamber and to the alcohol tray. In order to get an optical background, black dye is added to the alcohol layer on the bottom. The chamber is illuminated by flash tubes near the ends of the top window and the light is reflected by mirrors (13) at 45° into the sensitive layer.

In order to reduce the time spent in scanning to find the events, a special projector was devised in which the image of the length of the sixfoot cloud chamber is compressed to a length of about 18 in. in the projected image, while perpendicular distances remain full size. In addition to saving up to 75 percent scanning time, this method has several other advantages, for instance, small angular deflections of longitudinal tracks are magnified 4 to 5 times so that deflections as low as 1°can be detected easily.

In U.S.A. other high pressure diffusion cloud chambers have been made at Berkeley and Chicago, in each case in connection with high energy accelerators. Thus Elliott, Maenchen, Moulthrop, Oswald, Powell, and Wright[25]) describe a 36 atm diffusion cloud chamber for use

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[24]) W. B. Fowler, R. P. Shutt, A. M. Thorndike and W. L. Whittemore, Rev. Sci. Inst. 25 (1954) 996.

[25]) J. B. Elliott, G. Maenchen, P. H. Moulthrop, L. O. Oswald, W. M. Powell and R. W. Wright, Rev. Sci. Inst. 26 (1955) 696.

with the 184 in. cyclotron and the bevatron in Berkeley. The diffusion cloud chamber is built into a magnet giving a field of 21 000 oersted every 11th second, with a duration of the field of about 0.2 sec. The outside diameter of the chamber is 19.23 in. and the useful diameter of the sensitive region is 10 in. with a height of 2 to 2.5 in.

At the University of Chicago Schluter[26]) studied the $n + p \rightarrow d + \pi^0$ reaction with a similar diffusion cloud chamber connected to the 170 in. cyclotron. The field strength was 10 500 oersted. As all the semagnetic field equipped chambers in Brookhaven, Berkeley, and Chicago are of a similar type, it might be sufficient here to describe the one in Chicago[27]). A vertical section of this 30 atm hydrogen filled chamber is shown in fig. 10, where the text to the figure might be sufficient to make the construction clear. Fig. 11 shows the position of the cloud chamber in the iron yoke and fig. 12 shows schematically the temperature control of the system. The temperature of the bottom of the chamber is kept at —55° to —60°C by means of an acetone (or later methylene chloride) circulation system shown schematically in figs. 12–14. The liquid flows through a spiral passage (R in fig. 10, see also figs. 13 and 14) attached to the bottom of the cloud chamber and is cooled in a small heat exchanger by evaporating liquid nitrogen. With the circulating liquid at —75° C, the temperature of the pool of alcohol in the bottom of the chamber is about

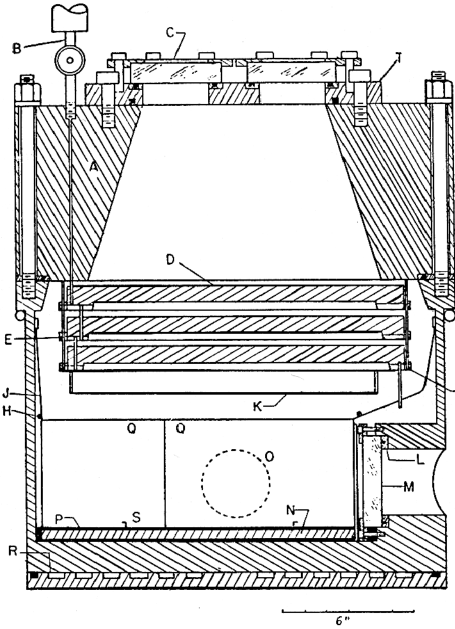

Fig. 10. Vertical section of the high-pressure diffusion cloud chamber in Chicago. A. Top pole, part of the iron yoke (fig. 11). B. Alcohol insertion. C. Camera window. D. Wick. E. Alcohol trays, F. Circultaion tubing. G. Tray heater. H. Thin wall heater. J. Thin wall. K. Clearing electrode. L. Soft copper ring. M. Tempered glass window. N. Copper plate. O. Beam entrance window. P. Dyed alcohol pool. Q. Mirrors. R. Grooves for acetone circulation. S. Fiducial markers. T. Top cover plate. Schluter and Wright (Rev. Sci. Inst. 26 (1955) 1053).

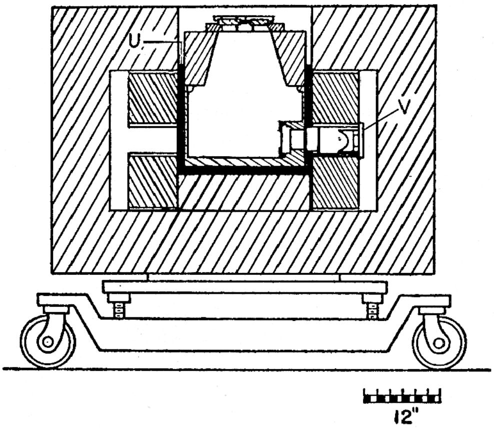

Fig. 11. Magnetic yoke of the Chicago diffusion cloud chamber. Schluter and Wright (Rev. Sci. Inst. 26 (1955) 1053).

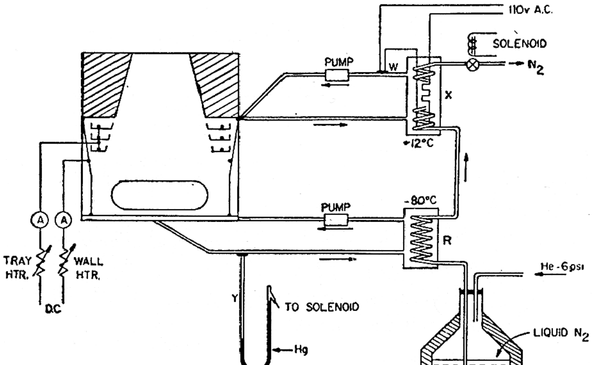

Fig. 12. Schematic diagram of the Chicago chamber thermal control system. Schluter and Wright (Rev. Sci. Inst. 26 (1955) 1053).

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[26]) R. A. Schluter, Phys. Rev. **96** (1954) 734.

[27]) R. A. Schluter and S. C. Wright, Rev. Sci. Inst. **26** (1955) 1053.

—55°C, that is, the temperature loss through the bottom is about 20°C†. The top temperature was kept at +12°C. The height of the sensitive layer was $2\frac{1}{2}$ to 3 inches.

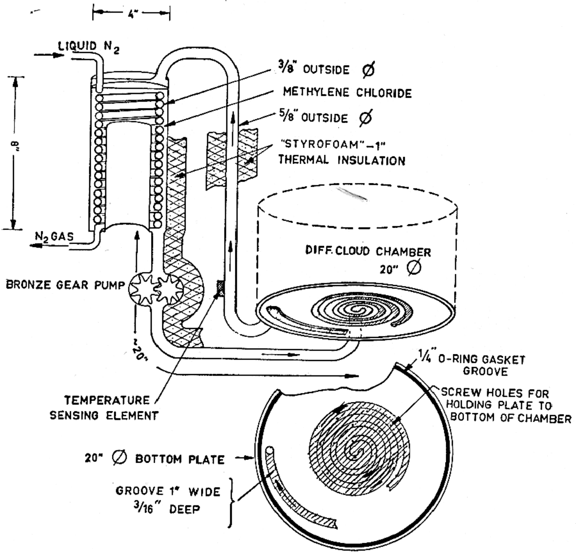

Fig. 13. Schematic detail of the Chicago chamber cooling system, according to a sketch obtained by the courtesy of Dr. R. A. Schluter.

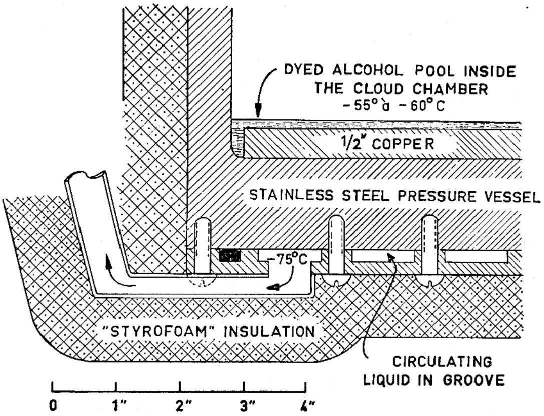

Fig. 14. Schematic detail of the Chicago chamber bottom plate, according to a sketch obtained by the courtesy of Dr. R. A. Schluter.

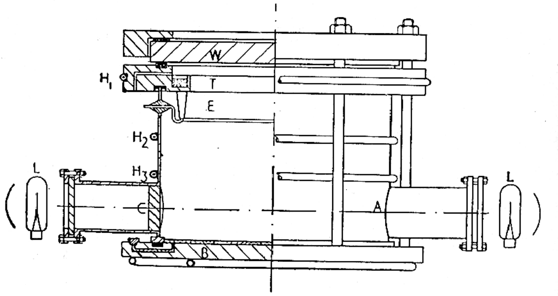

Fig. 15. Schematic drawing of Snowden's and Bevan's experimental 4 atm diffusion cloud chamber. T. Brass trough for alcohol. H$_1$. Heater for this trough, which is insulated from top and walls. W. Glass window. E. Ring electrode, supported by insulators from the bottom of the trough. H$_2$, H$_3$. Heaters for the temperature gradient control. L. 500 W projector lamps. C. Perspex lenses to diverge light into a 60° fan-shaped beam. B. ½ inch thick copper sheet cooled by methanol circulated from a heat exchanger cooled to —75 C° with solid carbon dioxide. The chamber wall made of $^1/_{16}$ inch mild steel (J. Sci. Inst. 30 (1953) 3).

In connexion with the high energy physics programme at Harwell Snowden and Bevan[28]) built a small 9 in. diameter diffusion cloud chamber to study the operating characteristics and to form the basis of a design for an 18 in. diameter chamber operating with hydrogen at 24 atm. Fig. 15 shows schematically the experimental cloud chamber. The details are explained in the text to the figure. With methanol and air at 1 atm, a sensitive layer of 1 in. in height was easily obtained, but in order to increase this to 2–3 in., control of the temperature gradient by means of the heaters H$_1$, H$_2$, H$_3$ and the use of a clearing field were required. The best results ($2\frac{1}{2}$–3 in. sensitive height) were obtained with the wall heaters adjusted to give a gradient of 9°C/cm and a field potential of —1200 V. Both argon and nitrogen gave results similar to air. Successful operation at pressures up to 4 atm was achieved.

In Liverpool Crewe and Evans[29]) built a 30 atm diffusion cloud chamber for the 156 in. synchrocyclotron, and recently Margaret Alston, Crewe, Evans, and v. Gierke[30]) have made a quite new chamber, used to investigate the production of $\pi^+$-mesons in p-p collisions at 383 MeV. The 18 in. diffusion cloud chamber is shown schematically in fig. 16a and photographically in fig. 16b. The details might be clear from the text to the figures. The chamber is

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† R. A. Schluter, personal communication.

[28]) M. Snowden and A. R. Bevan, J. Sci. Inst. **30** (1953) 3.

[29]) A. V. Crewe and W. H. Evans, Atomics **3** (1952) 221.

[30]) Margaret H. Alston, A. V. Crewe, W. H. Evans and G. von Gierke, Proc. Phys. Soc. A **69** (1956) 691.

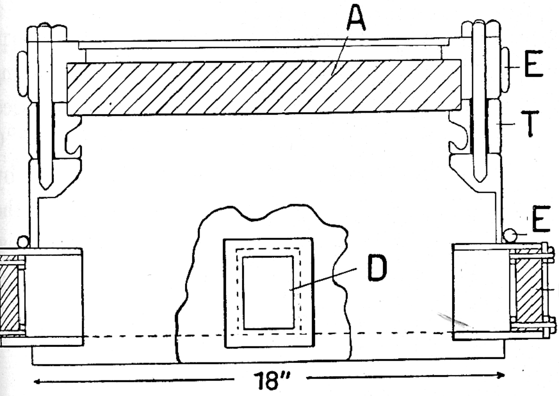

Fig. 16a. Schematic drawing.

filled with 28 atm of hydrogen and works in a magnetic field of 11 200 oersted. The base of the chamber is cooled to —60°C by passing cold acetone through copper pipes soft-soldered to the base. The temperature gradient in the sensitive region is 5°C/cm for hydrogen at 20–28 atm, and 7.5°C/cm for air at 1 atm. The sensitive depth is 2½–3 in.

In addition to these large diffusion cloud chambers numerous small chambers have been described[31–36]) and built in many places. Thus, fig. 17 shows a low pressure chamber[36]), made by the author and used for the study of the spontaneous fission of $Cf^{252}$. Figs. 18 and 19 show some fission tracks obtained in this chamber. The pressure of the airmethanol gas mixture was 0.2 atm and the depth of the sensitive layer about 1½ in. (without heaters). When photographed, the tracks were illuminated by means of a commercial xenon flash light tube, "Brown-Hobby" type BH 100. The xenon tube was then placed in front of a reflector in the cover F (fig. 17).

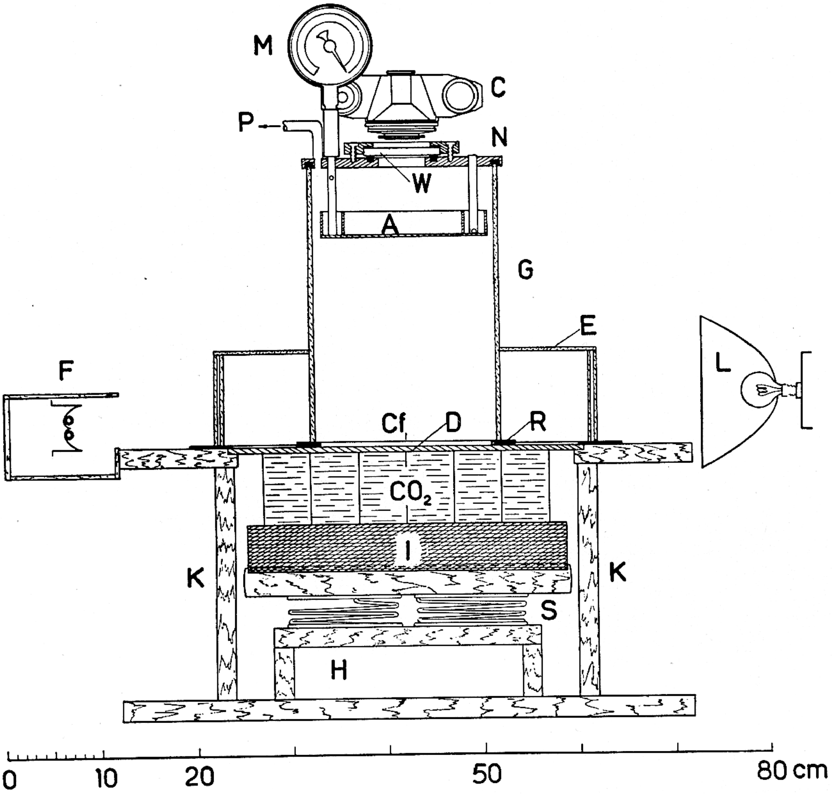

Fig. 17. Design of a low pressure diffusion cloud chamber used for the study of the spontaneous fission of $Cf^{252}$. A. Brass trough for alcohol. M. Pressure gauge. W. Window. C. Camera. N. Filling pipe. G. Glass cylinder. E. Heat insulating glass box (Slätis, Arkiv f. Fysik **10** (1956) 479).

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[31]) A. J. Barnard and J. R. Atkinson, Nature **169** (1952) 170.

[32]) A. L. Kuehner, J. Chem. Educ. **29** (1952) 511.

[33]) A. Voisin, J. Phys. et Rad. **14** (1953) 459.

[34]) T. Wilner, Elementa **36** (1953) 265.

[35]) A. B. Milojević, M. A. Cerineo, and B. J. Lalović Bull. Inst. Nucl. Sci. "Boris Kidrich" **3** (1953) 23.

[36]) H. Slätis, Arkiv f. Fysik **10** (1956) 479.

## 6. Some Properties of the Diffusion Cloud Chamber

### 6.1. FORMATION OF "RAIN"

Already Langsdorf[8]) payed much attention to the formation of rain of condensation which was apparently not dependent on the presence of ions. Cosmic and gamma rays produce nearly as many ions in the upper part of the chamber as in the sensitive region. The ions in the upper part will diffuse downward until they are condensed upon to form a diffuse rain, unless they are removed by an electric sweep field. However, it does not seem to be possible to remove completely the rain by an electric field. Presumably also light induces some photochemical action which creates condensation nuclei. Rain condensation not dependent upon the presence of ions might be caused in connexion with the bubbling of boiling liquid, contact of boiling liquid and a metal surface etc.[8]). The formation of rain increases the alcohol consumption and decreases the supersaturation in the lower layers, thus decreasing the sensitivity of the chamber.

Cowan[17]) also treats the formation of rain. Streamers of droplets will sometimes be produced by leaks that permit contaminated air from the outside to enter the chamber, or by the formation of coronas from fine points when a high voltage is used.

Bevan[14]) finds that if the alcohol temperature in the trough is raised to its boiling point, fine streamers of descending rain are produced, probably due to the evolution of large numbers of neutral condensation nuclei from tiny bubbles.

Thus in order to avoid rain formation, care should be taken in the construction of the sweeping field, the trough temperature should not be too high, and the chamber should, of course, be airtight, even if the pressure is 1 atm.

### 6.2. THE HEIGHT OF THE SENSITIVE REGION

The use of metal walls with heaters for the control of the temperature gradient in the cloud chamber made it possible to increase the height of the sensitive layer. However, for layers higher than about 3 in., an increase of the height is counterbalanced by a decrease in the sharpness of the tracks. Also, the method of decreasing the bottom temperature cannot be extended below —70° C. A decrease from —70° to —90° C increases the height of the sensitive layer by about ¾ in., it is true, but the tracks in the bottom layer are very thin because of the low vapour pressure in this region[23, 35]).

### 6.3. TRACK RECORD CAPACITY OF THE DIFFUSION CLOUD CHAMBER

Already Langsdorf[8]) pointed out that the diffusion cloud chamber during long periods can show tracks only for ionizations of the same order of magnitude as the normal background of ionization in an unshielded chamber. As mentioned before, this was confirmed by Miller, Fowler, and Shutt[21]). Hence, it is advantageous to shield the chamber from local gamma-radiation[8]). On the other hand, there is no limitation in the chamber's capacity to record bursts of radiation if an electric sweeping field is applied during the intervals[21]).

### 6.4. THE SAMPLE HOLDER

Rigid bodies in the sensitive region of the chamber will be condensed upon. This phenomenon is very disturbing, if one wants to investigate the radiation from a radioactive sample put into the chamber and especially for α-particles, as these will be absorbed by the condensed alcohol layer. The formation of this layer can be prevented by heating the sample holder, either electrically or by heat radiation. However, this will give rise to a small, disturbing convective current and hence a small insensitive region in the vicinity of the sample (see figs. 18 and 19).

## 7. Some Examples of the Use of the Diffusion Cloud Chamber

Shutt, Fowler, Miller, Thorndike, and Fowler[22]) at Brookhaven determined the cross section for the scattering of 60 MeV $\pi^-$-mesons by protons using their high pressure diffusion cloud chamber (similar to that in fig. 8) in connexion with the Columbia University Nevis cyclotron. The

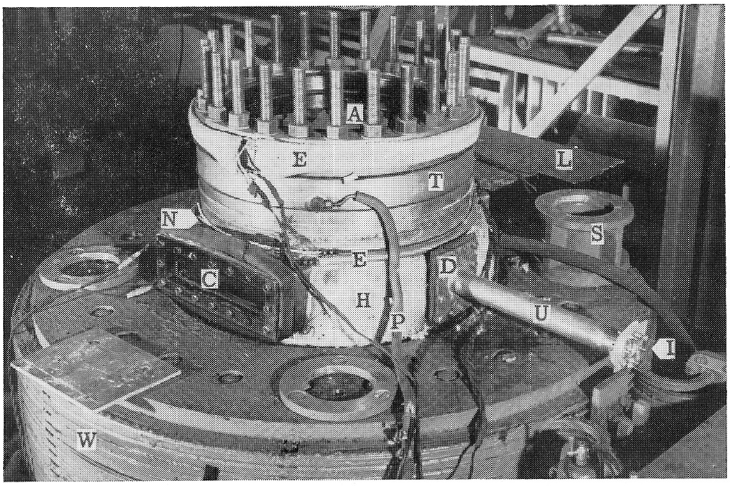


Fig. 16b. Photograph of the new Liverpool 18 inch diffusion cloud chamber (top coil removed). (Alston, Crewe, Evans and von Gierke, Proc. Phys. Soc. A **99** (1956) 691). A. Top window. T. Alcohol tray. C. Side window. D. Beam entry port. $E_1$ N. Heaters. H. Insulating glass wool jacket. P. Filling pipe. U. Extension tube. I. 0.006 inch duraluminium. S. Support for the (removed) top coil. W. Bottom field coil. The figures were obtained by the courtesy of Dr. Margaret H. Alston.

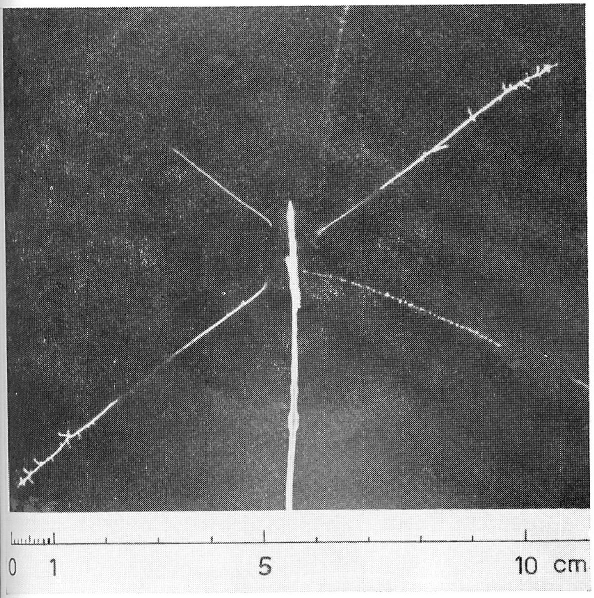


Fig. 18. Fission tracks (emitted in opposite directions) and two $\alpha$-tracks from Cf$^{252}$. The $\alpha$-track to the right is older than the others and is disappearing. The sample is held by a copper wire (the heavy vertical line). Pressure 0.2 atm Slätis[36].

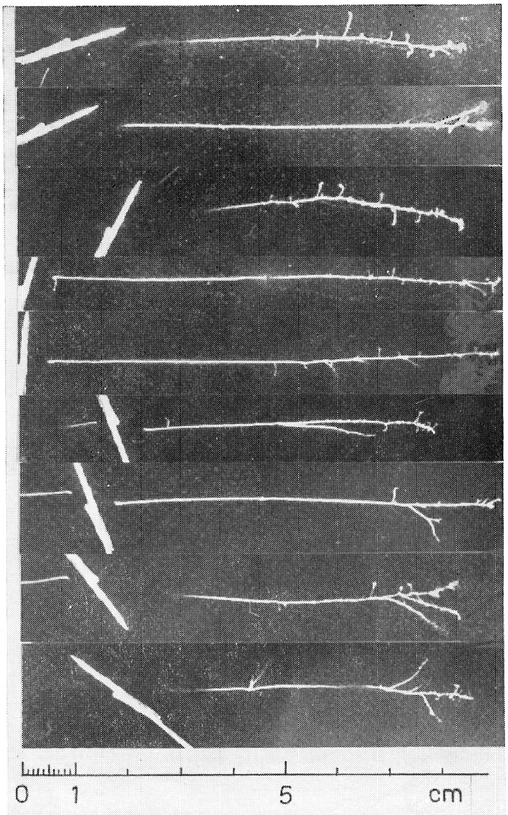
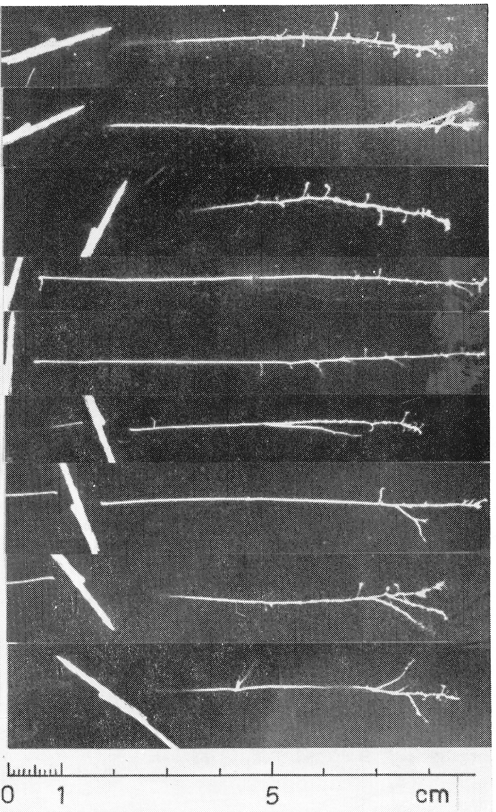


Fig. 19. A number of fission tracks from Cf$^{252}$. The heavy line to the left is the sample. The range of the fission track decreases, when the number of branches increases. Pressure 0.2 atm Slätis[36].



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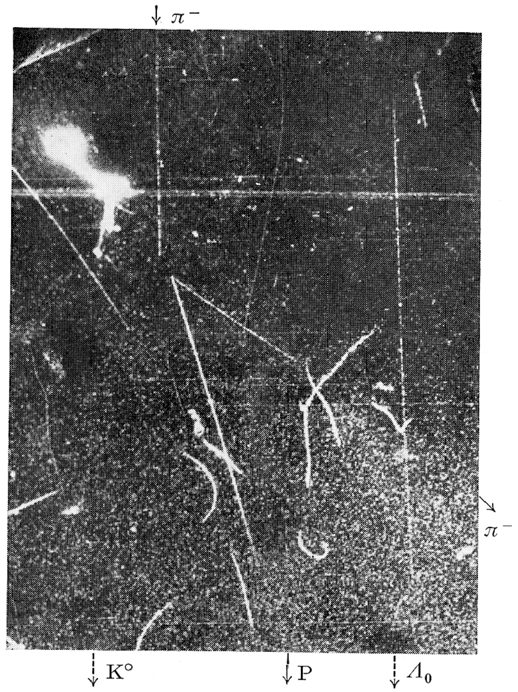

Fig. 21

Fig. 21. A neutral hyperon $\Lambda_0$ is produced in a collision between a 1.5 GeV from the Brookhaven Cosmotron and a proton in 20 atm of hydrogen in a diffusion cloud chamber. The $\Lambda_0$ particle is produced at the point where the $\pi^-$ ceases to ionize, its electric charge being neutralized by that of a proton. This $\Lambda_0$ decays into a proton (p) and a $\pi^-$ after living for $4 \times 10^{-11}$ seconds. If only one single neutral particle is assumed to conserve momentum and energy of incident $\pi^-$, its mass would have to be 1300 electron masses and its direction of flight as indicated by (K°). The picture was obtained by the courtesy of Dr. R. P. Shutt and earlier published. Fowler, Shutt, Thorndike, and Whittemore (Phys. Rev. **91** (1953) 1287).

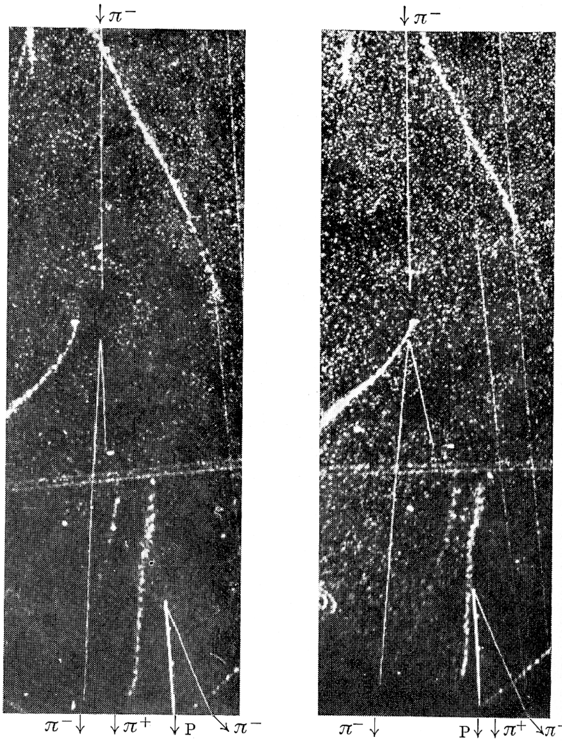

Fig. 22a.

Fig. 22b.

Fig. 22. Simultaneous production of a $\Lambda_0$ and a $\vartheta^0$ by a Cosmotron-produced 1.5 GeV $\pi^-$ in a hydrogen-filled diffusion cloud chamber. The collision takes place where the incident $\pi^-$ track disappears abruptly. The decay products of the $\vartheta^0$ are visible a short distance away t$\pi^-$, $\pi^+$). Further down, the decay products of (he $\Lambda_0$, (p, $\pi^-$) can be seen. The pictures were obtained by the courtesy of Dr. R. P. Shutt and earlier published. Fowler, Shutt, Thorndike, and Whittemore (Phys. Rev. **93** (1954) 861).

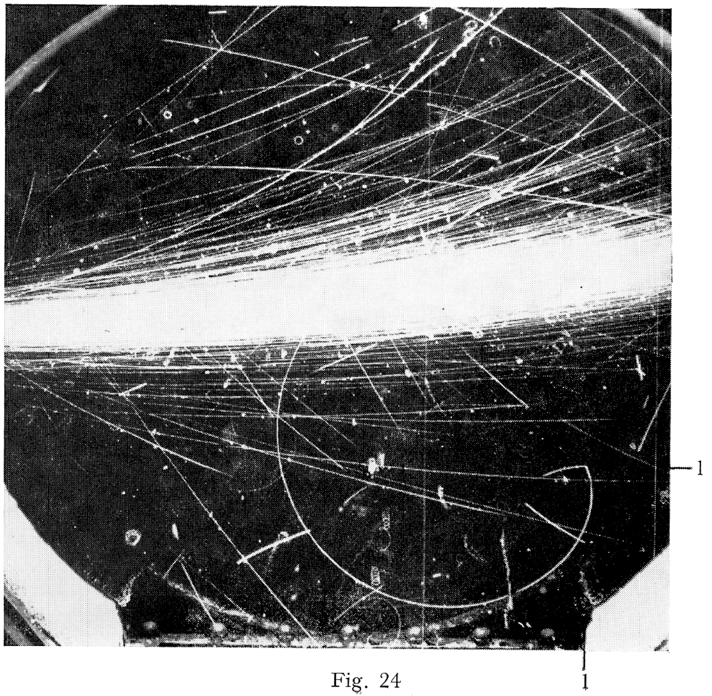

Fig. 24

Fig. 24. About 20 000 protons of 380 MeV energy enter the Liverpool diffusion cloud chamber. The G-shaped track is produced by a $\pi^+$-meson, which decays at the point (1.1) into a $\mu^+$-meson. Field strength 11 200 oersted. The picture was obtained by the courtesy of Dr. Margaret H. Alston, and earlier published. Alston, Crewe, Evans, von Gierke (Proc. Phys. Soc. A **69** (1956) 691).

chamber was filled with 21 atm of hydrogen and methanol. The cyclotron ion source was pulsed every 4 to 6 sec, and the 5600 stereoscopic pictures taken during the first day's operation were examined. Each picture showed about 20 tracks. Three cases were observed, which could be considered to be $\pi^-$-p scatterings. Fig. 20 shows one of these events. In a similar way the cross section was determined for the scattering of 50-MeV $\pi^+$-mesons by helium38).

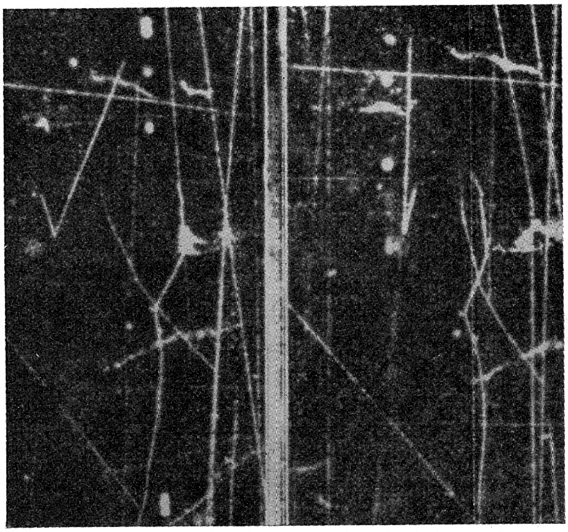

Fig. 20. Stereoscopic view of a $\pi^-$-p scattering event. A $\pi^-$ (thin track) from below, a recoil proton (short track) and a scattered pion are seen in the middle of the right hand picture, a bit to the left on the left hand picture. Shutt, Fowler, Miller, Thorndike, Fowler (Phys. Rev. **84** (1951) 1247).

In the high pressure diffusion cloud chamber exposed to a neutron beam from the Cosmotron at Brookhaven Fowler, Shutt, Thorndike, and Whittemore41) observed two $\Lambda_0$ particles, which decay according to $\Lambda_0 \rightarrow p + \pi^- + Q$. For $Q$ the values $39 \pm 16$ and $37 \pm 8$ MeV, respectively, were found in both cases. The cloud chamber was filled with 18 atm of hydrogen and methanol. In addition, Fowler, Shutt, Thorndike and Whittemore43) found that 1.5 GeV $\pi^-$-mesons from the Cosmotron produce $\Lambda_0$ particles in collisions with protons. Figs. 21 and 22 show such events.

The Berkeley Bevatron giving 6.2 GeV protons might be expected to produce more mesons than the Brookhaven Cosmotron. This is indeed the case. High energy neutrons were obtained by bombarding copper with protons. The erarlier mentioned high pressure cloud chamber was placed 75 feet from the target along a line tangent to the proton beam. The neutron energies extended from a few MeV up to 6.2 MeV. Among more than 500 events showing pion production in n-p collisions, there was one with seven outgoing prongs (fig. 23), 5 of them interpreted as pions, two as protons.

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37) H. Slätis, Kosmos **34** (1956) 33.

38) A. M. Thorndike, E. C. Fowler, W. B. Fowler and R. P. Shutt, Phys. Rev. **85** (1952) 928.

39) E. C. Fowler, W. B. Fowler, R. P. Shutt, A. M. Thorndike and W. L. Whittemore, Phys. Rev. **86** (1952) 1053.

40) K. A. Brueckner, Phys. Rev. **86** (1952) 106.

41) W. B. Fowler, R. P. Shutt, A. M. Thorndike and W. L. Whittemore, Phys. Rev. **90** (1953) 1126.

42) W. B. Fowler, R. P. Shutt, A. M. Thorndike and W. L. Whittemore, Phys. Rev. **91** (1953) 758.

43) W. B. Fowler, R. P. Shutt, A. M. Thorndike and W. L. Whittemore, Phys. Rev. **91** (1953) 1287; **93** (1954) 861.

44) W. B. Fowler, R. M. Lea, W. D. Shephard, R. P. Shutt, A. M. Thorndike and W. L. Whittemore, Phys. Rev. **92** (1953) 832.

45) R. C. Cornelius, C. P. Sargent, M. C. Rinehart, L. M. Lederman and K. Rogers, Phys. Rev. **92** (1953) 1583.

46) C. P. Sargent, R. Cornelius, M. Rinehart, L. M. Lederman and K. Rogers, Phys. Rev. **98** (1955) 1349.

47) C. P. Sargent, M. Rinehart, L. M. Lederman and K. C. Rogers, Phys. Rev. **99** (1955) 885.

Fig. 24 shows a proton beam exposed in the above mentioned Liverpool diffusion cloud chamber (fig. 16a and b).

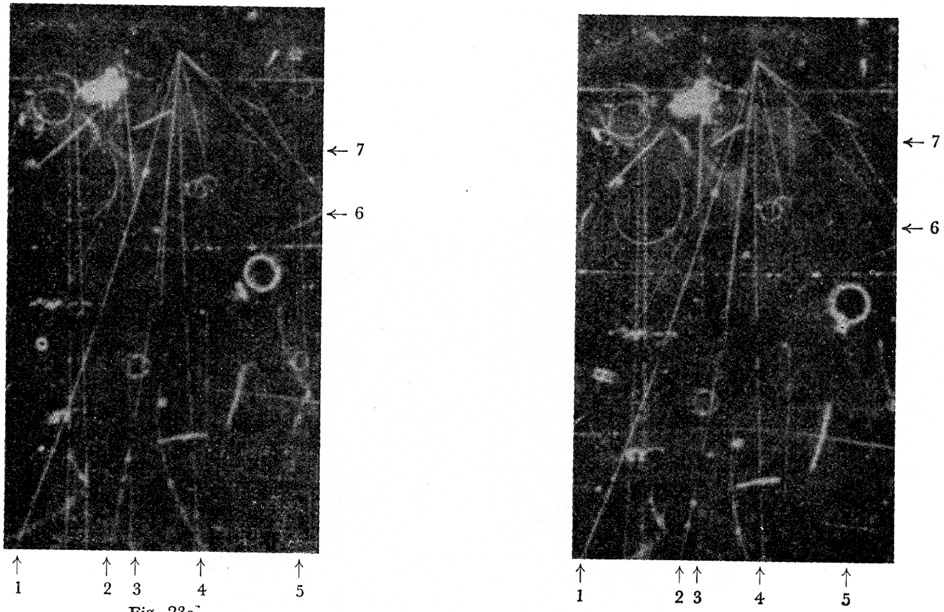

Fig. 23a

Fig. 23b

Fig. 23. $\pi$-meson production with neutrons from the Berkeley Bevatron. Tracks 1 and 5 are protons, tracks 2 and 6 are $\pi^+$-mesons, while tracks 3, 4 and 7 are $\pi^-$-mesons. Fowler, Maenchen, Powell, Saphir, Wright, (Phys. Rev. **101** (1956) 911).

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[48] M. C. Rinehart, K. C. Rogers and L. M. Lederman, Phys. Rev. **100** (1955) 883.

[49] R. A. Schluter, Phys. Rev. **96** (1954) 734.

[50] W. B. Fowler, G. Maenchen, W. M. Powell, G. Saphis and R. W. Wright, Phys. Rev. **101** (1956) 911.

[51] M. Snowden, The Diffusion Cloud Chamber, Progress in Nuclear Physics **3**, Editor O. R. Frisch (London, 1953) p. 1.