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A Study on a Contaminated Cloud Chamber.

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During a cloud chamber experiment now in progress in this laboratory we had for some time trouble with what we called „the ghost of Lord Rutherford": contamination due to traces of a radioactive substance which was probably present here ever since Rutherford performed his pioneer experiments in these rooms and which was picked up accidentally when the chamber was dismantled. We used this opportunity to take a series of photographs with different cleaning fields in order to illustrate their effect.

The large horizontally-operating cloud chamber has a quadratic section of about 57 cm side length and a depth of about 15 cm. A box containing counters and absorbers divides it in about $\frac{2}{3}$ of its height. The chamber was filled with oxygen at atmospheric pressure, and a mixture of 50% ethyl alcohol and 50% water was used as vapour-producing liquid. For the series of photographs reported here it was triggered by a telescope of three large counters, one above the chamber, one in the middle box and one below. Each photograph contains, therefore, at least one penetrating cosmic ray particle.

The cleaning field was varied between 3 V/cm and 30 V/cm. This produces a most striking difference in the photographs; with the lowest field so many old α-particle tracks are left in the chamber that a further reduction of the cleaning field is almost impossible if distinguishable tracks are desired. We show examples of these photographs in Plate 1—5, corresponding to cleaning fields of 3, 6, 12, 20 and 30 V/cm. The photographs speak for themselves; the progressive cleaning is unmistakable.

As a base for more quantitative considerations we have counted the numbers of all α-particle tracks and of all electron tracks (excluding the telescope particle or particles) on all the photographs of the series. The results are given in Table 1.

The table contains in the first column the values of the cleaning field in V/cm, in the second the average number N_e of observed electron tracks per photograph, in the third the average number N_α of α-tracks per photograph. The meaning of the values N_{cal} (calculated numbers of α-tracks per photograph) in the fourth column will be given later.

Table 1.

Field in V/cm	N_e	N_α	N_{cal}
3	12	67	63,5
6	19	32	33,2
12	22	15	17,9
20	20	12	11,9
30	21	10	9,0

Plate 1
3 V/cm

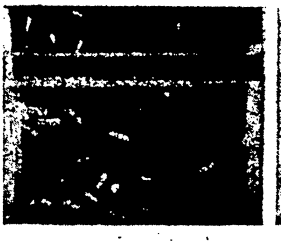


Plate 2
6 V/cm

Plate 3
12 V/cm

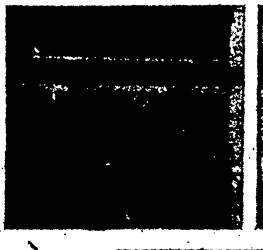
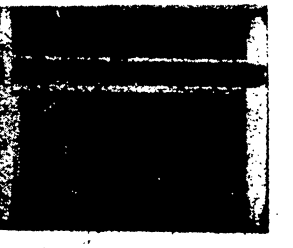


Plate 4
20 V/cm



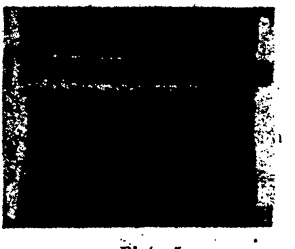


Plate 5
30 V/cm

We can use these figures at first to determine the time delay Δt between expansion and illumination, and the rate of occurence N_0 of α-particles per second. Tracks will be recorded if they were formed within a time interval t_m before the expansion*)

$$t_m = \frac{d}{\mu \cdot E} \tag{1}$$

(d = depth of the chamber, μ = mobility of the ions, E = intensity of the cleaning field). The number of tracks to be expected in the photograph is then

$$N_\alpha = \lambda N_0 (t_m + \Delta t), \tag{2}$$

where λ is the ratio of the volume of the illuminated part of the chamber to the total volume, in our case about 42%. As the quantities t_m can be calculated from (1) we can plot the observed numbers of tracks against t_m. This graph should be a linear function and permits us the determination of both N_0 and Δt (for the calculation an average value of the mobilities of positive and negative ions has been used). The plot is given in Fig. 1.

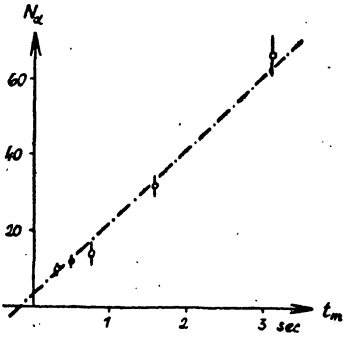


Fig. 1.

The resulting values are

$$\lambda N_0 = 20{,}6; \quad N_0 \sim 50,$$
$$\Delta t = 0{,}14 \text{ sec}.$$

Introducing these values in (2) we get the quantities N_{cal} of Table 1. The very satisfactory agreement is, of course, only another expression for the linearity of the $N_\alpha - t_m$ graph of Fig. 1. The value of 0,14 sec for the delay of the light flash, however, agrees very well with our expectations. The delay had not been measured accurately before, but we estimated it to about 0,1—0,2 sec.

Our findings about the number of electron tracks lead us to considerations of a more general interest. Although it may be possible that, owing to the large number of α-tracks in the 3 V/cm — photographs a few electron tracks had been overlooked, the actual reduction of the number of electron tracks in this case to almost $\frac{1}{2}$ of the number for large cleaning fields cannot be explained in this way. It must obviously be due to a reduction of the time of sensitivity to

*) This expression is sufficiently correct, as the central part of the chamber is illuminated, so that almost no tracks formed within the interval t_m will be lost.

a period shorter than the delay Δt between expansion and flash. Of course, the faint electron tracks will not be recorded if they are not produced either during this period or immediately before the expansion; it must be remembered that a track formed for instance at a time of the order Δt before the expansion would have a width of more than 3 mm and would certainly not be clear enough to be identified in our survey.

Thus the question arises whether and how the presence of contamination α-particles influences the sensitivity time of our chamber. One would be tempted, at a first guess, to think of exhaustion of the vapour in considerable parts of the chamber owing to the condensation along the α-tracks. However, a simple estimate shows that this cannot be the cause; the diffusion processes involved would be far too slow. Yet there remains a second influence of the tracks on the surrounding gas: through the heat produced by the condensation on the track ions. It is, of course, not mainly by convection that this heat will act upon the gas of the chamber. Only the immediate neighbourhood of the condensed drops — we shall denote it, in the following, by „track volume" — will be directly heated to a considerable extent. But the consequent expansion of the „track volume" will result in an adiabatic pressure increase of the „rest of the chamber" which, ultimately, might well bring the pressure in the chamber beyond the threshold value above which tracks cannot be formed. Thus the point in question is: Could the amount of liquid condensed in the α-tracks be large enough to produce a pressure increase in the rest of the chamber sufficient to exceed the maximum pressure of track formation?

To answer this question we calculate the work δA connected with this pressure increase, which must be equal to the heat Q produced in the condensation process. If we denote the initial pressure and volume of the chamber gas by P_1 and V_1, the corresponding quantities after an expansion with an expansion ratio $(1 + r)$ by P_2, V_2, and with the minimum expansion ratio $(1 + r - \delta r)$ by P'_2, V'_2, we can write down this work leading from a state (P_2, V_2) to (P'_2, V'_2):

$$\delta A \approx P_2 (V_2 - V'_2) = P_2 \, \delta V = P_1 V_1 (1 + r)^{-\gamma} \, \delta r, \qquad (3)$$

as for our purposes the pressure change δP

$$\delta P = P'_2 - P_2 = P_1 (1 + r - \delta r)^{-\gamma} - P_1 (1 + r)^{-\gamma} = \\ = \gamma P_1 \, \delta r \, (1 + r)^{-1-\gamma} \qquad (4)$$

can be neglected compared with $P_2 \cdot \gamma$, the ratio of the specific heats, has to be calculated for the mixture of chamber gas, water vapour and alcohol vapour from

$$\frac{1}{\gamma - 1} = \frac{1}{\gamma_0 - 1}\frac{P_0}{P} + \frac{1}{\gamma_w - 1}\frac{P_w}{P} + \frac{1}{\gamma_a - 1}\frac{P_a}{P}, \qquad (5)$$

where P_0, P_w, P_a are the partial pressures of oxygen, water vapour and alcohol vapour, γ_0, γ_w, γ_a the corresponding values of c_p/c_v, and P the total pressure. With our values, $P_1 = 76$ cm Hg, $V_1 = 4{,}2 \cdot 10^4$ cm^3, and $(1 + r) = 1{,}13$, $\delta r = 0{,}01$, we find $P = 1{,}2$ cm Hg, $\gamma = 1{,}36$, and hence

$$\delta A = Q = 3{,}8 \cdot 10^8 \text{ erg} = 9{,}05 \text{ cal}. \qquad (6)$$

As the latent heat of vaporisation q of our mixture at the temperature concerned is about 330 cal, we find for the mass of liquid due to be condensed in order to produce this heat

$$m = Q/q = 2{,}7 \cdot 10^{-2} \text{ gr}. \qquad (7)$$

We have to compare this with the amount of „condensable" supersaturated vapour in the track volume, as this vapour is the main, and in a first approximation the only, source from which the tracks can draw the material for condensation. To determine it we need the over-all density of supersaturated vapour, which is with sufficient accuracy given by the difference in the equilibrium states of vapour densities at T_1 and $T_2 = T_1 (1 + r)^{1-\gamma}$. Taking $T_1 = 290°$ we get $T_2 = 277{,}5°$, and with the corresponding vapour pressures ($p_1 = 1{,}44$ and $3{,}75$ cm; $p_2 = 0{,}63$ and $1{,}70$ cm for water and alcohol) from

$$p_1 V_1 = (M_1/M)\, RT_1 \text{ and } p_2 V_2 = (M_2/M)\, RT_2 \qquad (8)$$

the mass $\delta M = M_1 - M_2$ of the supersaturated vapour

$$\delta M = 2{,}16 \text{ gr}, \qquad (8a)$$

and hence the density ϱ_s of the supersaturated vapour

$$\varrho_s = 4{,}6 \cdot 10^{-5} \text{ gr/cm}^3. \qquad (8b)$$

We define as „track volume" for a single track the volume of a cylinder, the length of which is the track length and its diameter the „90%-thickness" as defined by Blackett[1])

$$x = 4{,}7\sqrt{Dt} \qquad (9)$$

where D is the diffusion coefficient of the ions in the gas ($D = 0{,}032$ in our experiment). This is certainly a rather conservative estimate, as the track volume considered above means the gas surrounding and feeding the drops. The volume $v(t)$ of a track formed at a time t before the expansion is then

$$v(t) = \frac{\pi}{4} \cdot (4{,}7\sqrt{Dt})^2 \cdot R. \qquad (10)$$

The range R was measured; it is about 6 cm. (10) becomes then

$$v(t) = 3{,}33 \cdot t \text{ cm}^3 \tag{10a}$$

and the total volume V_α of all tracks formed within the interval t_m, with a production rate of $N_0\,\mathrm{d}t$ in $\mathrm{d}t$

$$V_\alpha = \int_0^{t_m} v(t) \cdot N_0\,\mathrm{d}t = 1{,}66_5 N_0 \cdot t_m^2. \tag{11}$$

For the lowest field intensity of 3 V/cm t_m becomes about 3,2 sec, and thus

$$V_\alpha = 850 \text{ cm}^3. \tag{11a}$$

This volume contains a mass m' of supersaturated vapour

$$m' = \varrho_s V_\alpha = 3{,}9 \cdot 10^{-2} \text{ gr} \tag{12}$$

which is slightly more than the amount sufficient to suppress track formation. Thus, even if no heat would diffuse into the gas from the walls, the heat produced in the tracks alone could bring the pressure in the chamber above the critical value $P_2 + \delta P$. This bears out the correctness in principle of our assumption that under the conditions prevailing in our chamber the contamination may reduce the sensitivity time in an appreciable measure. Whether or not it proves to be an actual limitation depends, however, on the rate of heat production in the tracks — in other words, on the growth of the drops.

Unfortunately, no considerations of a stringent character can be made about this growth in our case. Quantitative statements can only be based on the assumption that the individual drops grow in an unchanging atmosphere of vapour, and this is obviously not correct even before the drops have consumed all the supersaturated vapour available in the „track volume". As a first approximation, however, we may use this method and can expect from it results of the right order of magnitude.

If we accept Hazen's[2]) figures for the equilibrium growth

$$d(r_0^2)/\mathrm{d}t \sim 5 \cdot 10^{-6} \text{ cm}^2\text{sec}^{-1} \tag{13}$$

we get a drop volume after a time of growth

$$v_d = 4{,}7 \cdot 10^{-8} \cdot \tau^{3/2}. \tag{13a}$$

For the number of drops in one track we may assume, allowing for recombination, $N_d = 2 \cdot 10^5$. With a density ϱ_e of the condensing liquid we find for the mass of liquid contained in all the drops of all tracks

$$m'' = N_0 t_m \cdot N_d v_d \cdot \varrho_e \tag{14}$$

which becomes for the smallest field used

$$m'' = 1{,}3 \cdot \tau^{3/2}. \tag{14a}$$

The end of the sensitivity will be reached when the heat developed by the condensation of m'' stops the conditions of track formation, or $m'' = m$. This gives for maximum sensitivity time owing to contamination

$$\tau_s^{3/2} = m/1{,}3 = 2{,}1 \cdot 10^{-2};\ \tau_s = 0{,}076 \text{ sec.} \qquad (15)$$

This value should obviously be considered as a lower limit, although the exact value is probably not much larger. However, if we take in account the heating from the walls also, we are certainly right to expect a „total" sensitivity time not exceeding 0,1 sec for the contaminated chamber with small cleaning field.

A further support of this result comes from a discussion of the numbers of electron tracks. One would be tempted to compare the values for two different cleaning fields and, neglecting the unlikely contribution of tracks formed considerably before the expansion, to assume their numbers to be proportional to the sensitivity times (15) with (14). This leads to

$$N'_e/N_e = \tau'_s/\tau_s = (t_m/t'_m)^{3/2} = (E'/E)^{3/2} \qquad (16)$$

and with $N_e = 12$ for $E = 3$ V/cm, $N'_e = 19{,}25$ for $E' = 6$ V/cm we have

$$N'_e/N_e = 1{,}60;\ (E'/E)^{3/2} = 1{,}59. \qquad (17)$$

However, this apparently striking agreement must be considered as a chance result of fluctuations and compensating neglections, as in the case of the larger field the correcthess of our basic assumptions is at least very doubtful.

It is more promising to compare the number of electron tracks for the 3 V/cm-field with the „saturation" number of tracks for the largest fields, when the chamber certainly remains sensitive for longer than the delay of the light. This „saturation number" is about 21, as seen in Table 1 (which value agrees, incidentally, quite satisfactorily with the background of random cosmic ray tracks to be expected in our chamber for a delay time of about $\frac{1}{6}$ sec). If the „saturation number" N_s corresponds to the number of cosmic ray particles passing through the chamber during the time Δt (= 0,14 sec), the reduced number N_e to the shortened sensitivity time $\tau_s = \alpha \cdot \Delta t$, and if tracks appearing within an interval t_0 before the expansion are still recorded, we have

$$\frac{N_e}{N_s} = \frac{\alpha \cdot \Delta t + t_0}{\Delta t + t_0} = 12/21 = 0{,}57 \qquad (18)$$

which leads to $\alpha < 0{,}57$, or a maximum sensitivity time (with $\Delta t = 0{,}14$ sec)

$$\tau_s < 0{,}08 \text{ sec.} \qquad (18a)$$

Again, of course, statistical fluctuations and neglections may change this value somewhat. The limits due to the — statistical and subjective, through uncertainty of identification — error of N_e for instance would lead to a probable error in τ_s of about $\pm$ 0,025. On the other hand, introducing (15) as a minimum value of τ_s we can show that our assumption $t_0 \ll \Delta t$ is well justified: the resulting value of t_0 is about 1,3 . 10^{-2} sec. Of course, even a small error in Δt will change this value very considerably, but not its order of magnitude — which is all we need to prove again that all the counted electron tracks are really very recent, and that the sensitivity time of the chamber is shortened to about 0,1 sec if a cleaning field of only 3 V/cm is used.

We may furthermore show that even with a large cleaning field the α-tracks could still appreciably shorten the sensitivity time, and possibly even be the factor that decides its limits. If no contamination is present a chamber of the dimensions and conditions described here should have a sensitivity time of about 1—2 seconds. The heating effect of α-tracks formed during this period, however, would probably exceed the „permitted" 9 cal.

To attempt a quantitative treatment we have again to use the formulae for independent growth of the drops, which in this case is certainly not correct. Still, with this approximation we get for a drop of an age τ a volume according to (13a). If tracks are produced with a rate $N_0\,dt$ within dt, the total drop volume in all tracks is

$$V_d = \int_0^{\tau_s} N_d v_d(\tau) \,.\, N_0\,d\tau = 0{,}19\tau^{4/3}. \qquad (19)$$

This represents a limitation of the sensitivity time if the mass of the drops of V_d reaches m in (7), i. e. if $\varrho_e \,.\, V_d = m$, which gives

$$\tau_s^{4/3} = 0{,}17;\ \tau_s = 0{,}49 \text{ sec}, \qquad (19a)$$

a value really appreciably below the „normal" sensitivity time. However, owing to the crudeness of the approximation used this value may be wrong — too small — even by an order of magnitude. Yet it is noticeable that even then the influence of the sensitivity time of the heat generated in the α-tracks, or better the consequent compression of the gas in the chamber through the expansion of the gas surrounding the tracks, is not negligible, but at least one important factor for the limitation of the sensitivity time of the chamber.

Finally, we may add yet another test of the reliability of our estimates by checking the time scale in an independent determination of the age of the tracks. This can be done by measuring the thicknesses of the tracks in our photographs and comparing them with Blackett's „90%-thicknesses" (9). Again, of course, we should expect not more than a semi-qualitative result, as neither the measu-

rement of an α-track thickness can avoid a certain arbitrariness, especially for old tracks, nor can it be claimed that the „thickness" recorded in our photographs should represent exactly the 90%-diffusion limit. It may even be that our method introduces a systematical difference in the measurements on old and on more recent tracks. However, none of these possible errors will change the time scale very much, so that we are satisfied with our procedure as long as no precision measurements are aimed at, but estimates only.

If α-particles are emitted within an interval $0 \leqq t \leqq t_m$ with a constant production rate N_0, and if the thickness of their tracks is given by (9), we expect a number $N(x)\,\mathrm{d}x$ of tracks to have a thickness between x and $x + \mathrm{d}x$

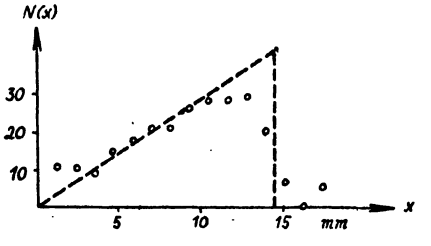


Fig. 2.

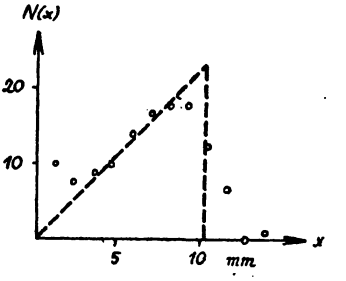


Fig. 3.

$$N(x)\,\mathrm{d}x = \frac{2\lambda N_0 \,.\, x \,.\, \mathrm{d}x}{(4{,}7\sqrt{D})^2} \quad \text{if } x \leqq 4{,}7\sqrt{Dt_m},$$
$$N(x)\,\mathrm{d}x = 0 \qquad \text{if } x > 4{,}7\sqrt{Dt_m} \tag{20}$$

(disregarding the thin tracks formed between expansion and flash). In Fig. 2 and 3 we have compared the calculated distribution (20) for the cleaning fields 3 V/cm and 6 V/cm with the distributions found in the photographs. The agreement is as good as it can reasonably be expected; the „tail" of apparently too thick tracks may not only be due to the inaccuracy of the measurements. At least partly it should be due to the slower motion of the positive ions which will remain in the chamber a little longer than the maximum time t_m calculated with average ion mobility. The excess of very thin tracks, on the other hand, is due to α-particles emitted between expansion and illumination, which are disregarded in (20).

References:

(1) P. M. S. Blackett, Proc. Roy. Soc. (A) 146, 281 (1934).
(2) W. E. Hazen, Rev. Sci. Instr. 13, 247 (1942).

Studie se znečištěnou Wilsonovou komorou.

(Obsah předešlého článku.)

Na universitě v Manchesteru jsou nyní prováděny pokusy s Wilsonovou komorou, která byla znečištěna stopami radioaktivních látek, jež jsou v laboratoři přítomny pravděpodobně od časů Lorda Rutherforda, který zde prováděl své důležité pionýrské výzkumy.

Nejprve byl zkoumán vliv elektrického pole, odstraňující ionisační produkty z komory (cleaning field) na četnost pozorovaných částic α a elektronů. Zjistilo se, že v přítomnosti značného počtu částic α nastává pokles viditelnosti elektronových stop. Byly proto prozkoumány — jak theoreticky tak i experimentálně — možné příčiny tohoto zjevu. Pravděpodobnou příčinou jest vznik tepla kondensací páry podél stopy částice α, který způsobí adiabatický vzrůst tlaku uvnitř komory nad hodnotu, při které se ještě mohou tvořit stopy.