Physics. — *"Further experiments with liquid helium. Z. Magnetic researches. XXVIII. Magnetisation of anhydrous $CrCl_3$, $CoCl_2$ and $NiCl_2$ at very low temperatures."* By H. R. WOLTJER and H. KAMERLINGH ONNES.

§ 1. *Introduction.* In the preceding communication the magnetic anomalies shown by anhydrous $CrCl_3$, $CoCl_2$ and $NiCl_2$ at the temperatures of liquid hydrogen have been pointed out. It seemed to be important to extend this research to the very low temperatures obtainable with liquid helium. The following questions came to the foreground: as regards $CrCl_3$ whether the initial susceptibility would increase with decreasing temperature as strongly as in the liquid hydrogen region and whether in strong fields saturation phenomena would appear; for the other substances whether the decrease of the susceptibility with decreasing temperature that seemed to be indicated by the measurements in liquid hydrogen would be continued.

§ 2. *Method.* With the same samples to which the preceding communication refers, the magnetisation was determined from the attraction, exerted on a small quantity of the substance in an inhomogeneous magnetic field following exactly the method described in full in connection with the investigation of gadoliniumsulphate [1]).

§ 3. *Results.* For $CrCl_3$ two series of measurements in helium have been carried out and three in liquid hydrogen; for each of both other substances one series in liquid helium followed in each case by a measurement in liquid hydrogen.

It seems superfluous to give here all the figures concerning $CrCl_3$. In table I we give part of the series of 12 and 15 July 1922. These observations have been plotted in fig. 1. The curves in that diagram have been obtained by smoothing the *whole* observational material. This smoothing was performed thus: with the aid of the preliminary isotherms the curves $H = $ constant have been drawn in a σ, T-diagram (σ is the specific magnetisation, H the field strength after correction for demagnetisation) (fig. 2) and from this the final σ, H-diagram has been traced.

In table II are given the forces (in grammes) exerted on the samples of $CoCl_2$ and $NiCl_2$ (resp. 0.2990 and 0.2515g.) at different temperatures

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[1]) These Proc. **26**, p. 614; Leiden Comm. N^0. 167*b*.

TABLE I.   CrCl₃

T	20°.3 K		14°.6		4°.23		2°.36		1°.23	
H	σ	H	σ	H	σ	H	σ	H	σ	
2.6 Kg.	11.5	2.5	25.2	2.3	35.2	2.3	36.0	2.3	36.3	
5.1	22.5	5.0	38.2	4.8	47.3	4.8	48.6	4.8	49.4	
7.7	31.1	7.5	49.1	7.4	57.3	7.4	58.6	—	—	
10.1	38.3	9.9	57.4	9.8	66.5	9.8	66.9	9.8	67.2	
13.7	45.4	13.5	65.3	13.3	77.1	13.3	78.0	13.3	78.8	
16.3	49.4	16.0	68.2	15.9	83.0	15.9	84.2	15.9	85.1	
17.5	51.7	17.3	69.9	17.1	86.3	—	—	17.1	88.5	
18.1	52.7	17.9	70.6	17.7	88.0	17.7	89.5	—	—	
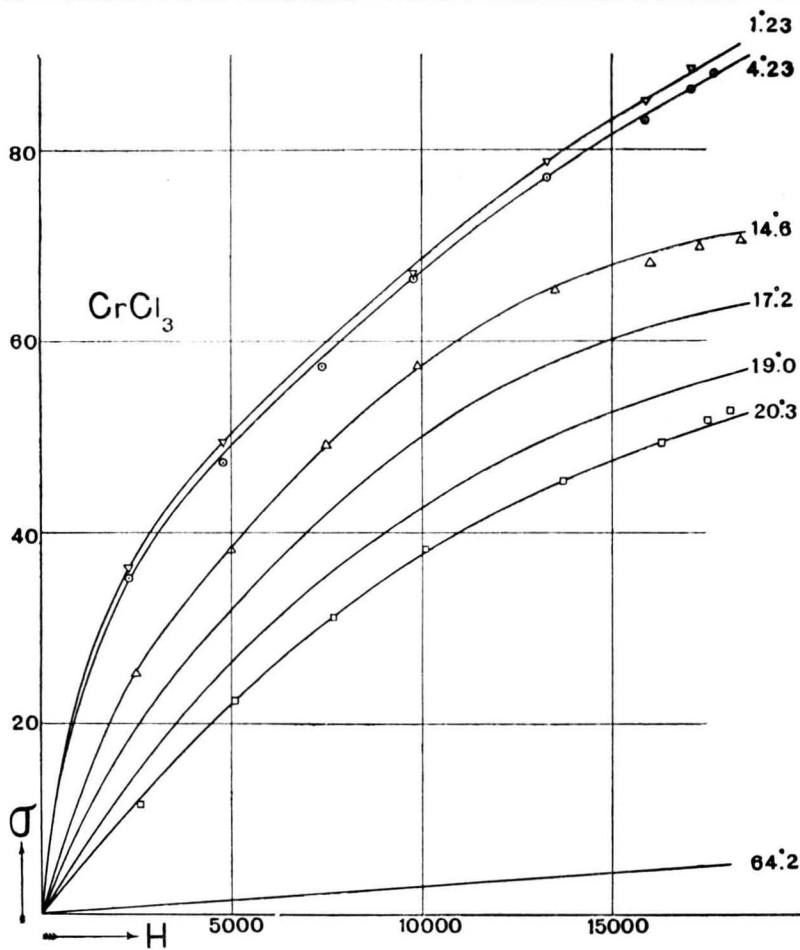
Fig. 1.
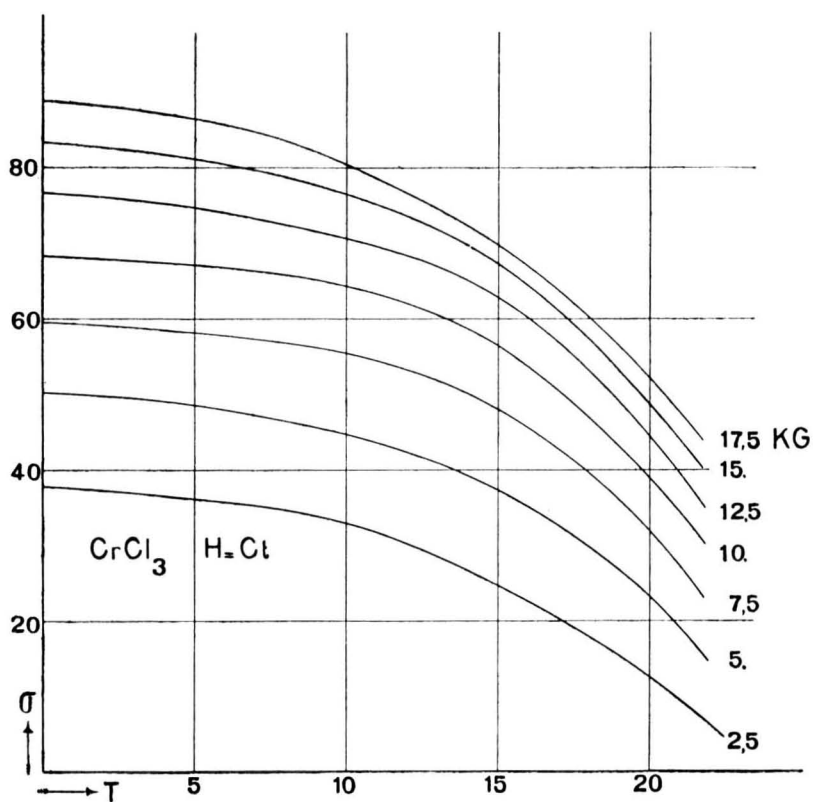
Fig. 2.

TABLE II.

I	3	4	5	10	15	20	30	45	60	70
CoCl$_2$										
20°.4 K	—	—	0.9	3.9	9.9	17.9	31.9	41.9	45.4	—
14.0	—	—	0.8	3.8	9.6	17.6	31.6	41.6	45.2	46.8
4.2	—	—	0.8	3.7	9.5	17.7	31.8	41.8	45.4	47.1
2.31	—	0.4	0.7	3.7	9.5	17.7	31.7	41.8	45.4	47.1
1.48	—	—	—	—	—	—	32.2	—	45.9	—
NiCl$_2$										
20.4	—	—	0.3	1.3	3.0	5.4	9.6	12.5	13.8	—
14.6	—	—	0.3	1.3	3.0	5.4	9.7	12.5	13.8	—
4.22	—	—	0.3	1.2	3.0	5.3	9.5	12.6	13.7	14.3
2.30	0.11	0.18	0.3	1.2	3.0	5.2	9.6	12.5	13.8	14.3
1.48	—	—	—	—	2.9	—	—	—	13.8	14.3

and different currents in the magnetcoils. It shows that the change of the susceptibility is very small for $CoCl_2$ and entirely out of the experimental accuracy for $NiCl_2$. The magnetisation being so slightly dependent on temperature, in table III and in figs. 3 and 4 only one magnetic isotherm is given, that for 2.°3 K. [1]).

TABLE III, $T = 2°.3 K.$

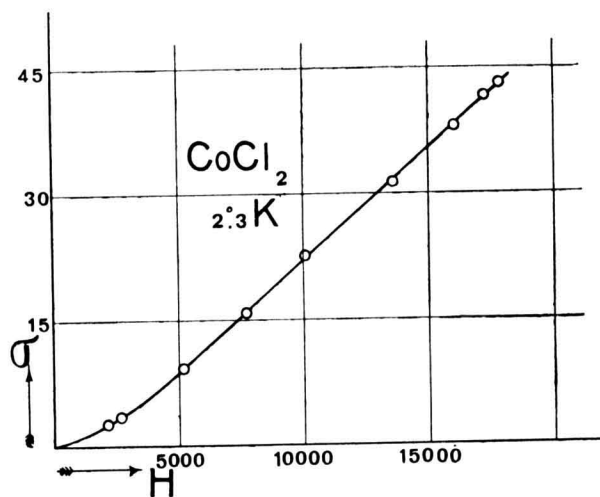| NiCl₂		CoCl₂	
H	σ	H	σ
1.6	1.1	—	—
2.2	1.3	2.2	2.6
2.7	1.6	2.7	3.5
5.2	3.6	5.2	9.1
7.7	5.7	7.7	15.8
10.2	7.9	10.1	22.5
13.7	11.3	13.6	31.3
16.2	13.6	16.1	38.0
17.4	14.9	17.3	41.2
18.0	15.6	17.9	43.1

Fig. 3.

[1]) If σ over H is taken, values for χ are found slightly different from those given in table IV of the preceding communication for $CoCl_2$ and $NiCl_2$ at 14°.2 K., even if the circumstance is taken into account, that in table III of the present communication corrections
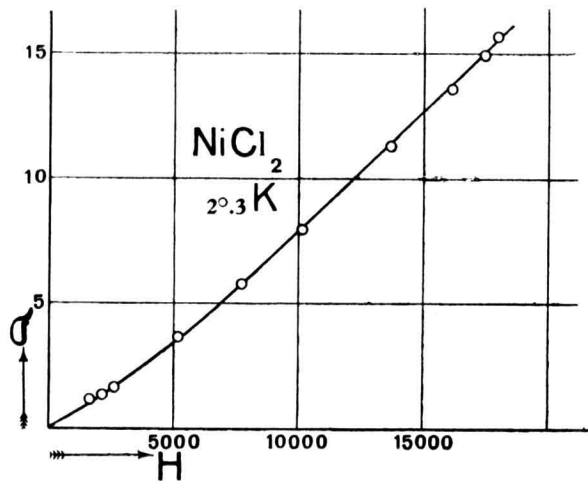
Fig. 4.

§ 4. *Discussion.* The magnetisation curves show some resemblance to those found by WEISS and FORRER [1] for nickel in the neighbourhood of the CURIE-point, but there are also striking differences: there is no question of saturation magnetisation and the slope of the isotherm for large fields is at helium temperatures even greater than at hydrogen temperatures [2]. WEISS's theory of ferromagnetism does not seem to be applicable here. The highest specific magnetisation attained by us is 89.5 e. m. C.G.S. corresponding to 12.6 magnetons, and the saturation would correspond to 18 magnetons. Neither for $CrCl_3$ nor for the other chlorides have we found hysteresis or residual magnetism.

For $CoCl_2$ and $NiCl_2$ the magnetisation curves are for smaller fields convex to the H-axis, for larger ones nearly linear; the susceptibility approaches asymptotically a limit for large fields. Formally, this feature may be explained thus: the magnetisation may be considered to be a result of two components, one proportional to the field strength (in the diagram it would be represented as a straight line through the origin

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for the demagnetisation are applied. Nearly as large differences are found, if, not the calculated susceptibilities, but the values of the attraction at hydrogen temperatures found here are compared with those on which the χ-values of table IV on the preceding communication are based. The present observations have been made by means of a different apparatus and on another occasion to those of the preceding paper. The latter are no doubt more accurate, but the former are better comparable with the observations in liquid helium, since they are taken within a small interval of time, using the same method and the same apparatus. As regards $NiCl_2$ the differences remain nearly within the accuracy of the experiments (about $2^0/_0$), for $CoCl_2$ they are larger (above $4^0/_0$) and not yet quite explained.

[1] Paris C.R. 178, p. 1046.

[2] This remark only holds if the large magnetisation of the $CrCl_3$ does not influence the distribution of the lines of force and the calibration of the large magnet remains valid.

parallel to the straight part of the curve); and a second in the opposite direction to the field, which develops under influence of the field from zero to a maximum amount. However it seems difficult to see the physical meaning of this last component. As regards $CrCl_3$ the measurements do not favour the conclusion that there is a limit to the susceptibility; there seems to be no reason for replacing the last parts of the curves for $1°.23$ and $4°.23$ K in fig. 1 by straight lines. If there was a limit, one could perhaps think of a superposition of paramagnetism and ferromagnetism, as recently found by PESCHARD [1]).

For $CrCl_3$ it seems important to investigate the magneto-caloric effect in order to ascertain whether there is yet a spontaneous magnetisation notwithstanding the absence of saturation phenomena [2]).

§ 5. *Summary*.

1. For anhydrous $CrCl_3$, $CoCl_2$ and $NiCl_2$ the magnetisationcurves have been determined at the temperatures of liquid hydrogen and helium, at which temperatures these substances are below their "CURIE-temperature" [3]).

2. $CrCl_3$ shows ferromagnetism in so far as the susceptibility decreases with increasing field strength; saturation spontaneous magnetisation, or hysteresis has not been found.

3. $NiCl_2$ and $CoCl_2$ show an unusual type of magnetisationcurve, first convex to the H-axis, then linear for higher fields. At low temperatures the law connecting magnetisation and field strength seems to approach asymptotically to a definite form (different for $CrCl_3$ and for $CoCl_2$ and $NiCl_2$) and so to become independent of temperature; for $CoCl_2$ and $NiCl_2$ this form has been reached nearly at hydrogen temperature; for $CrCl_3$ there is only a small change in magnetisation on cooling from $4°.23$ to $1°.23$ K.

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[1]) Paris C.R. 180 (1925) p. 1836.

[2]) The lines $\tau = ct$ in a H, T-diagram from which, as shown by WEISS and FORRER for nickel, the spontaneous magnetisation also may be derived, do not give much information in our case, mainly on account of the temperature gaps above and below the liquid hydrogen region [note added in the translation].

[3]) Here by „CURIE-temperature" the temperature θ in the relation $\chi(T-\theta) = C$ is meant.