Physics. — *"Magnetic researches. XIV. On paramagnetism at low temperatures".* (Continuation of VII). By H. KAMERLINGH ONNES and E. OOSTERHUIS. Communication N°. 139e from the Physical Laboratory at Leiden. Communicated by Prof. H. KAMERLINGH ONNES.

§ 15. *Ferrous sulphate.* (Continuation of III § 2). The measurements of the susceptibility of paramagnetic substances at low temperatures were continued according to the method previously described.

Crystallized ferrous sulphate, which had been already investigated by KAMERLINGH ONNES and PERRIER (Comm. N°. 122a), was once more very carefully prepared, by precipitating it out of its aqueous solution with alcohol. The values of the susceptibility found do not entirely correspond to the previous ones, but the dependence on the temperature is precisely the same, as is shown by the following table, when compared with table 11 of Comm. N°. 122a,

TABLE XII.

Crystallized ferrous sulphate $FeSO_4 . 7H_2O$ precipitated with alcohol.			
T.	$\chi . 10^6$	$\chi . T. 10^6$	Bath
292.°3 K.	42.4	12390	in air
77.3	160	12370	} liquid
64.6	191	12340	} nitrogen
20.2 ·	571	11590	} liquid
14.7	756	11110	} hydrogen

§ 16. *Palladium.* Pure palladium (from HERAEUS) gave the following figures: (see p. 918)

Palladium, it will be seen, deviates markedly from CURIE's law. CURIE found just for this substance the law $\chi . T = $ const. fairly well confirmed. HONDA [1] (above ordinary temperature) and OWEN [2] (below ordinary temperature down to 100° K.) found deviations from CURIE's law which agree very well with our results. The line $\dfrac{1}{\chi} = f(T)$

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[1]) K. HONDA. Ann. d. Phys. 32, p. 1027, 1910.

[2]) M. OWEN. Ann. d. Phys. 37, p. 657, 1912.

TABLE XIII.

Palladium.		
T	$\chi \cdot 10^6$	Bath
291° K.	5.3	in air
250	5.8	liquid methyl chloride
212	6.0	liquid methyl chloride
170	6.9	liquid ethylene
77.3	8.1	liquid nitrogen
70.2	8.2	liquid nitrogen
64.6	8.3	liquid nitrogen
20.3	9.9	liquid hydrogen
17.9	10.2	liquid hydrogen
14.7	10.9	liquid hydrogen

shows some irregularities, which are greater than we should have expected considering the degree of accuracy of the experiments.

§ 17. *Ferric ammoniumsulphate (iron alum).*

This substance will be seen to follow Curie's law throughout the whole range of temperature that was examined. This, according to the theory developed by Oosterhuis in Suppl. No. 31, would be owing to the great moment of inertia which a molecule of this substance undoubtedly possesses.

It may also be explained by the theory which Foëx gives following Weiss (C. R. T. 157, p. 1145. 1913). In fact iron alum is a substance crystallizing in the regular system and according to Foëx, for such substances the line $\dfrac{1}{\chi} = f(T)$ will be a straight line at all temperatures.

This property of ferric alum may also be regarded from another point of view if we consider the latest results by Kamerlingh Onnes and Perrier (Comm. N°. 139d). In § 3 we pointed out that interposition of water molecules between the molecules of ferrous sulphate, as occurs when this salt crystallizes with water of crystallisation, causes the deviation from Curie's law to disappear, and thus diminishes Δ.

TABLE XIV.

Ferric ammoniumsulfate $Fe_2(SO_4)_3$. $(NH_4)_2SO_4 + 24H_2O$.			
T.	$\chi \cdot 10^3$	$\chi \cdot T. \, 10^3$	Bath
290.°0 K.	30.4	8820	in air
169. 6	51.8	8790	liquid ethylene
77. 3	114.7	8870	liquid nitrogen
64. 6	137.0	8850	
20. 4	432	8810	liquid hydrogen
17. 9	492	8810	
14. 7	598	8790	

We found the same in § 10 for manganese sulphate, and in § 11 we came to the conclusion that the decrease of Δ might be the consequence of an increase in the distance of the paramagnetic constituents of the salt. Finally we drew attention to the fact that the transition of oxygen from the gaseous to the liquid form might be accompanied by a change in Δ. PERRIER and KAMERLINGH ONNES have now demonstrated that Δ decreases with the dilution of oxygen with nitrogen, and that the change of Δ with the density, which must be assumed to find for liquid oxygen at all temperatures [with the help of the $\Delta_{p \, liq} \, T$ corresponding to the liquid density $\varrho_{liq} \, T$] from

$$\chi (T + \Delta_{p \, liq \, T}) = C$$

the same number of magnetons as in the gas at ordinary temperature, agrees well with the change of Δ with the distance of the molecules, which is found from the dilution of oxygen with nitrogen. By this it has become evident that if Δ is the consequence of the existence of a molecular field, this field decreases when the molecules are brought to a greater distance from each other, and soon, at molecular concentrations of about $\dfrac{1}{200}$, is no longer perceptible.

In ferric alum, the distance of the Fe-atoms is of the same order as that at which the molecular field of the oxygen molecules in the solution of oxygen and nitrogen disappeared in KAMERLINGH ONNES and PERRIER's experiments. That this substance conforms to CURIE's law as far down as the freezing-point of hydrogen, may therefore be due to the atoms of iron, at the *atomic concentration* in this substance, being at a distance which permits them to behave like

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those of a normal paramagnetic substance. Should this hypothesis be correct, it would be of importance to take notice of the atomic concentration, in studying paramagnetic substances. To determine the number of magnetons in a paramagnetic atom, we should therefore have to take (complex) compounds, which fulfil this condition of being sufficiently "diluted". This condition is fulfilled by many of the materials which have been used for the calculations about magnetons [1]).

' If we arrange the substances according to the value of their atomic concentration, we see that in general the deviations from Curie's law at low temperatures seem to appear sooner in substances with a high concentration. Oosterhuis's calculations (Comm. Suppl. N°. 31) give particulars of the amount of the deviation in different substances. It will therefore be desirable, if we want to determine the number of magnetons in an atom at low temperature, to go down to very small concentrations. This is no difficulty for the measurement, for, although the specific susceptibility at small concentration is small, it increases considerably according to Curie's law for a given concentration with the transition to low temperatures. We should come upon chemical ground if we were to discuss what compounds would be suitable for this purpose. Double salts and complex compounds seem to be particularly suitable, provided we are able to apply the correction for diamagnetism.

It is very likely that with high atomic concentrations Δ may rise to very high values. Something of this sort might be the case with platinum (see § 12) and with the ferromagnetic substances the investigation of which first led Weiss and Foëx to the introduction of a negative magnetic field.

For crystals, a "*linear* concentration" may have to be introduced. The value of Δ for different directions would have to be brought into connection with this.

In the further study of the deviation from Curie's law, use will have to be made of the results of Werner's investigation of the constitution of complex compounds on the one hand, and on the other hand of the data which experiments upon the diffraction of Röntgen rays, such as Bragg in particular has made, may yield. What these can teach concerning the arrangement of the atoms and the structure of the atomic lattice, is of great importance from the above point of view. (*To be continued*).

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[1]) In ferric alum is realised a case of solution of a paramagnetic in a practically neutral substance, of the same kind as that which Weiss considered by extrapolation in his discussion of the ferro-magnetic alloys when he was searching for the law of distance for the molecular field.