

Volume 10 Number 2 pages 85-180 April 1970

CRYOGENICS

the international journal
of low temperature
engineering and research

General editor
K MENDELSSOHN

American editor
B W BIRMINGHAM

European editor
J L OLSEN

Published by Iliffe Science and Technology Publications Ltd

CRYOGENICS is the international journal of low temperature engineering and research and publishes original papers on every aspect of the subject. Also published are original research and technical notes and letters to the editors. In consultation with the Staff Editor, each issue contains a small number of review articles. Notes on new equipment, production techniques, notices of forthcoming events and conference reports are also featured. The journal is published in alternate months (February, April, June, August, October, and December). The language of the journal is English.

Material intended for publication should be sent to the following addresses.

From Great Britain, Australia, New Zealand, the Middle East, the Far East and Africa

**Dr K. Mendelssohn, FRS,
The Clarendon Laboratory, Parks Road,
Oxford, England.**

From North and South America

**B. W. Birmingham,
National Bureau of Standards,
Boulder, Colorado 80302,
USA.**

From the Continent of Europe

**Professor J. L. Olsen,
Eidg. Technische Hochschule,
Gloriastrasse 35,
8006 Zurich, Switzerland.**

Enquiries relating to subscriptions and circulation should be sent to

**Subscription Department,
Cryogenics, Iliffe House,
32 High Street, Guildford,
Surrey, England.**

Subscription agencies overseas

Australia
Gordon & Gotch Ltd, 374-80 Lonsdale Street,
Melbourne, Victoria.

Canada
William Dawson Subscription Service Ltd,
6 Thorncliffe Park Drive,
Toronto 17, Ontario.

India
International Book House, Ash Lane,
Mahatma Gandhi Road, Bombay.

New Zealand
Gordon & Gotch Ltd,
75 Anzac Avenue, Auckland.

USA
Iliffe-NTP Inc.,
300 East 42nd Street, New York, NY 10017.

Subscription rate per annum

£15 or \$37.50

Price per issue

£2.10s. or \$6.25

General Editor
K. Mendelssohn

American Editor
B. W. Birmingham

European Editor
J. L. Olsen

Staff Editor
A. H. Crawford

Assistant Editor
P. A. Battams

Sales Manager
K. E. Macdonald

Advertisement Manager
T. Goldsmith

Advisory Editors
L. Bewilogua, *Dresden, Germany (E)*
G. Careri, *Rome, Italy*
K. D. Chaudhuri, *Delhi, India*
L. van Gerven, *Leuven, Belgium*
A. Lacaze, *Grenoble, France*
J. O. Linde, *Stockholm, Sweden*
O. V. Lounasmaa, *Helsinki, Finland*
K. Oshima, *Tokyo, Japan*
W. B. Pearson, *Ottawa, Canada*
R. Plank, *Karlsruhe, Germany (W)*
R. S. Safrata, *Rez, Czechoslovakia*
A. Shal'nikov, *Moscow, USSR*
B. Shinnar, *Tel-Aviv, Israel*
K. D. Taconis, *Leiden, Holland*
G. K. White, *Sydney, Australia*

Editorial and Advertisement Offices
Iliffe House, 32 High Street,
Guildford, Surrey, England.

Throughout the text of this journal various words are used which are Registered Trade Names. These are indicated usually by being printed with an initial capital.

Published by **Iliffe Science and Technology Publications Limited**,
*Iliffe House, 32 High Street,
Guildford, Surrey, England.*
Telephone: Guildford 71661

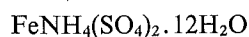
Printed in Great Britain by the Chapel River Press,
Andover, Hants.

© IPC Business Press Ltd 1970

The $T - T^*$ relation in ferric ammonium sulphate below 0.1 K

R. Yee and G. O. Zimmerman

In experiments involving adiabatic demagnetization it is usually convenient to use the cooling salt as the thermometer. This is done by measuring the magnetic temperature T^* of the cooling salt which is defined as C/χ where C is the Curie constant and χ the susceptibility after the demagnetization corrections, which transform the actual readings to those expected of a spherical sample, have been applied. In spite of the fact that



ferric ammonium sulphate (FAS), is used as the cooling salt in many instances, there is no agreement in the literature on the T^*-T relation of this salt below 0.1 K. For this reason, we have attempted to determine the relation below that temperature.

We have calibrated the magnetic susceptibility of FAS against $\text{Ce}_2\text{Mg}_3(\text{NO}_3)_{12} \cdot 12\text{H}_2\text{O}$, cerium magnesium nitrate (CMN), down to 0.033 K. We have chosen CMN as a secondary thermometer to measure the T^*-T relation below 0.1 K for FAS because it is well-known¹ that for CMN the magnetic temperature T^* is equal to the thermodynamic temperature T for temperatures above 0.006 K.

Simon and Kurti² have published data relating the magnetic temperature T^* , obtained from corrected susceptibility measurements, and the thermodynamic temperature T for ferric ammonium sulphate down to 0.020 K. According to their data, there is a spontaneous magnetic alignment at about 0.042 K. On the other hand, Steenland, deKlerk, Potters, and Gorter³ have been able to achieve temperatures as low as 0.030 K before observing a transition. Cooke, Meyer, and Wolf⁴ have also measured the T^*-T relation for FAS using CMN as a secondary thermometer. Unfortunately, the lowest temperature reached was only 0.045 K and consequently, their work does not provide any additional information on the transition temperature. In general, our results are

in agreement with Kurti and Simon, above 0.06 K. At lower temperatures our data is in better agreement with that of Cooke, Meyer, and Wolf⁴ and Steenland, deKlerk, Potters, and Gorter³ as far as no transition is observed.

Experimental procedure

The FAS salt was in the form of a cylinder measuring 1 in. in dia. by 3.5 in. long, and containing 2 000 strands of No. 39 copper enamelled wires. The FAS powder was bound to the wires and held together by means of GE #7031 varnish. The 2 000 strands of copper wire threading the salt, for temperature uniformity, were brought out at one end of the FAS salt form and attached to the CMN specimen. The CMN consisted of single crystal segments of cerium magnesium nitrate arranged to form a cylinder having its axis parallel to the ac measuring field. The crystalline c-axis was oriented normal to the ac measuring field. The segments were arranged so that single layers of the copper wires were interleaved between the CMN segments. GE #7031 varnish was used to cement the structure together.

A 45 Hz ac mutual inductance bridge, described elsewhere,⁵ was used for the susceptibility measurements with an appropriate switching arrangement to alternately connect the ac mutual inductance bridge to the FAS susceptibility coil, or the CMN susceptibility coil.

Low temperatures were reached by adiabatic demagnetization from helium temperatures starting usually at 1.2 K. The magnetic field was produced by a superconducting magnet which was removed after demagnetization to prevent interference with the susceptibility measurements.

The general procedure was an initial adiabatic demagnetization of the FAS and the CMN. After the FAS and the CMN had come into thermal equilibrium and began to warm-up, susceptibility readings were made alternately on the FAS salt and CMN salt. These readings were continued throughout the warm-up period until the two salts reached liquid helium temperatures, that is,

about 1 K. A typical warm-up time between the lowest temperature and 1.2 K was about 10 hours.

At this point, helium exchange gas was introduced into the vacuum can, and both the CMN and FAS calibrated against the helium bath pressure between 1.2 and 4 K.

Analysis and results

Since the sample of CMN used, weighing approximately 2 g, was quite insensitive to susceptibility changes in the liquid helium temperature range, it could not be calibrated directly using the high temperature susceptibility readings and the liquid helium bath vapour pressure data. Instead, the high temperature susceptibility data of the $\text{FeNH}_4(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$ salt was calibrated against the vapour pressure of the helium bath. Extrapolation of this temperature calibration for the lower temperature FAS susceptibility readings was performed using Curie's law and the T^*-T correction data, as given by Kurti and Simon,² as well as using the proper shape and packing correction factors.³ The T^*-T relation of Kurti and Simon for FAS was assumed to be correct above 0.1 K. Within the temperature range from 0.3 to 0.1 K, temperature values could now be assigned to the susceptibility readings of the CMN salt by using a linear interpolation of the FAS temperature scale, since the readings for the two salts were taken sequentially.

In order to extend the CMN temperature scale to the lower temperatures, a plot of the CMN susceptibility readings versus the inverse of the assigned temperature values in the temperature range from 0.3 to 0.1 K was constructed, followed by a least square fit analysis to a

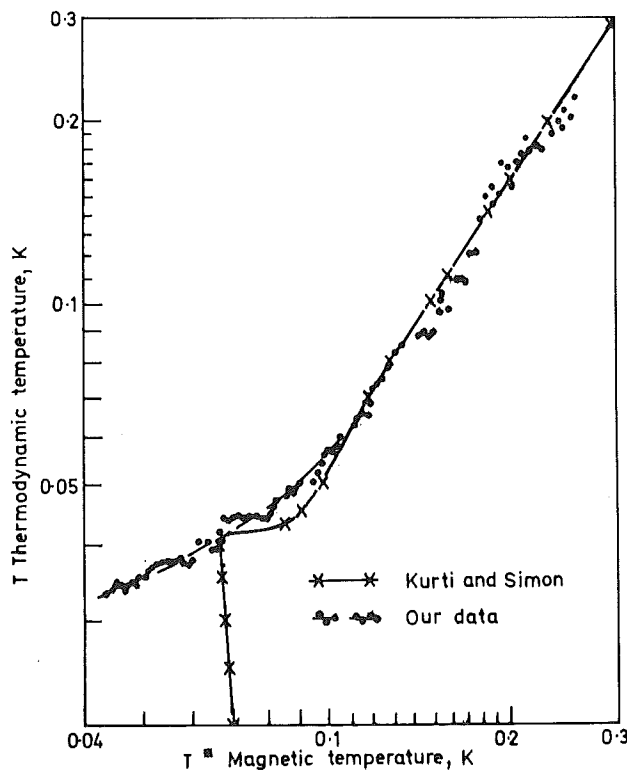


Figure 1. T^*-T relation for $\text{FeNH}_4(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$

Table 1. Temperature T versus magnetic temperature T^*

T	T^*	T	T^*
0.0338	0.0645	0.0451	0.0955
0.0340	0.0655	0.0474	0.0976
0.0335	0.0663	0.0490	0.0992
0.0328	0.0671	0.0497	0.1000
0.0328	0.0680	0.0497	0.1016
0.0339	0.0690	0.0509	0.1031
0.0343	0.0698	0.0528	0.1045
0.0350	0.0692	0.0549	0.1087
0.0372	0.0721	0.0556	0.1100
0.0373	0.0731	0.0571	0.1124
0.0370	0.0741	0.0583	0.1146
0.0371	0.0757	0.0583	0.1162
0.0374	0.0772	0.0625	0.1176
0.0377	0.0783	0.0664	0.1191
0.0378	0.0794	0.0677	0.1215
0.0382	0.0807	0.0694	0.1241
0.0382	0.0821	0.0741	0.1273
0.0382	0.0829	0.0783	0.1309
0.0392	0.0843	0.0817	0.1333
0.0404	0.0856	0.0860	0.1424
0.0412	0.0880	0.0873	0.1438
0.0418	0.0893	0.0866	0.1476
0.0417	0.0905	0.0872	0.1489
0.0421	0.0914	0.0952	0.1514
0.0432	0.0928	0.0964	0.1526
0.0432	0.0942		

straight line. The resulting straight line represents, therefore, the Curie law for the CMN sample; by extrapolating this line, the temperature scale for the susceptibility readings of the CMN salt could now be extended to the lower temperatures.

Finally, to obtain the T^*-T curve of the T^* values of the FAS salt pill and the thermodynamic temperature T , as obtained from the CMN salt, an interpolation procedure is used which is weighted according to the time interval between successive readings. The resulting T^*-T plot is shown in the accompanying figure along with the data of Kurti and Simon.² The results of Cooke et al.⁴ are not shown since they agree with our data within the scatter. Our results are similar to the results of Steenland, de Klerk, Potters, and Gorter³ in that no magnetic transition has been observed down to at least 0.033 K. Our data does show, however, a weak anomaly at about 0.04 K suggestive of some sort of interaction, but hardly as severe as the magnetic ordering transition given in the data of Kurti and Simon. It may be possible that this difference can be ascribed to the quality of the FAS salt specimens. Our FAS was reagent grade, obtained from Mallinkrodt Chemical Works, St Louis, and was used without any further purification. Experimental data points unsmoothed, below 0.2 K are also given in the table.

This work was supported in part by grant No. AF-AFOSR 1117-60, US Air Force Office of Scientific Research. We would like to thank Mr M. Taylor for his help in the data analysis.

REFERENCES

- DANIELS, J. M., and ROBINSON, F. N. H., *Phil. Mag.* **44**, 630 (1953); HUDSON, R. P., and KAESER, R. S. *Physics* **3**, 95 (1967)
- KURTI, N., and SIMON, F. *Proc. Roy. Soc. A* **152**, 1 (1935)
- STEENLAND, M. J., DEKLERK, D., POTTERS, M. L., and GORTER, C. J. *Physica* **17**, 149 (1951)
- COOKE, A. H., MEYER, H., WOLF, W. P. *Proc. Roy. Soc. A* **233**, 536 (1956)
- YEE, R., and ZIMMERMAN, G. O. *J. Appl. Phys* **37**, 3577 (1966)