Cryogenics

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George O. Zimmerman
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Dear Mr. Zimmerman:

Your paper, "Note on the Operation of Dilution Refrigerators in High Magnetic Fields," was sent to two referees. Both referees recommend the paper not be published in Cryogenics. The comments of these referees are enclosed. In view of these recommendations, we will not be able to accept the paper for publication.

You may want to rework your paper following the suggestions of the referees and resubmit it at a later time or to an alternate journal. If I can be of any assistance in that process please feel free to contact me.

I appreciate your consideration of Cryogenics as a possible journal for publication of your work.

Sincerely,

Alan F. Clark
American Editor, Cryogenics

Enclosure: Manuscript

Review of "Note on the operation---" by G. O. Zimmerman

This paper deals with the fact that a dilution refrigerator operating within a high magnetic field experiences a reduction in the cooling power due to the nuclear polarization of the circulating ^{3}He. This argument is essentially a dimensional argument since the thermodynamics of the dilution refrigerator are not treated precisely. He compares the formula for the cooling power given by Lounasmaa with an energy for polarization. Despite these shortcomings, I think the order of magnitude of the effect should be about right. However, in order to make the effect larger than it probably is, Zimmerman assumes that there is a large concentration gradient within the dilute phase in the mixing chamber. This is unrealistic.

I don't think that this paper adds much to the knowledge of dilution refrigeration. The work here is over simplified, while the proper treatment of cooling power of refrigerators has been done better elsewhere.

Review of " Note on the Operation...." by G. O. Zimmerman

The paper is ok as far as it goes: ie, it presents a simplified analysis of the operation of a dilution refrigerator in a magnetic field. Unfortunately the analysis is too simplified to qualify as a proper theoretical paper, and there is no experimental data so that the paper doesnt qualify as an experimental paper combined with a simple theoretical analysis. I therefore recommend rejection.

NOTE ON THE OPERATION OF DILUTION REFRIGERATORS IN HIGH MAGNETIC FIELDS

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ABSTRACT

This letter points out the limit of the lowest temperature achieved in a dilution refrigerator, if the mixing chamber and/or heat exchangers are exposed to high magnetic fields. This limit is due to the energy input which occurs when He^3 is polarized.

In the operation of dilution refrigerators[1] in high magnetic fields, many precautions have to be taken in order to minimize the heating of the sample and the refrigerator due to the magnetic field. Various sources of heat input have to be considered in which the magnet characteristics play an important role. Recently a thorough analysis of heat leaks and shielding in high magnetic fields was carried out by Meyer, Silvera and Brandt[2].

One of the main sources of unwanted heat input is eddy-current heating[2] which is proportional to the square of dB/dt where B is the magnetic field. This is particularly important if the magnet has a ripple. The ripple in a persistent current superconducting magnet is negligible, but it is significant in a Bitter Magnet[2]. Eddy-current heating can also be significant, even in a superconducting magnet, if there is relative motion between the magnet and the sample, so that if there is a field gradient, the sample finds itself in various fields. Another important source of heating is that due to mechanical vibrations. One also encounters dificulties in the transfer of heat between the mixing chamber and the sample.

In order to eliminate some of these difficulties, and to achieve the lowest sample temperature possible, some investigators have built dilution refrigerators whose mixing chambers are inside the magnet, and thus subject to the magnetic field. The sample is usually immersed in the helium mixture so that the sample is at the lowest temperature of the refrigerator. The mixing chamber is generally made out of an epoxy, a nonconducting material, in order to reduce eddy-current heating. This note is written to point out that in the configuration where the mixing chamber is subject to a high magnetic field, there is an extra significant source of heat which is due to the polarization of the He^3 nuclei. This heat source is proportional to the square of the applied field, and becomes quite significant at high fields. This effect may prevent the dilution refrigerator from achieving its lowest ultimate temperature.

Consider a refrigerator whose specifications are similar to those described in reference 1. The cooling power in watts is

$$\frac{dQ}{dt} = 84\frac{dn}{dt}T^2 \quad (1)$$

where dn/dt is the number of moles of He^3 circulating in the refrigerator and T is the absolute temperature. The energy which a He^3 atom gives up when aligning with the magnetic field is $2\mu B$ where μ is the magnetic moment of the nucleus and B is the applied magnetic field. This energy is equal to $2\times1.075B\times10^{-26}$ joules, if B is in Tesla. The fractional change in the magnetization of the atoms upon entering a magnetic field is then $2\mu B/kT_F$, where k is Boltzman's constant, and T_F is the Fermi temperature which for liquid He^3 at low pressure has the value of 0.359K[3]. For temperatures below T_F this is a valid approximation. The heat input per second due to the polarization of the concentrated phase of He^3 is then the number of atoms which is polarized times the energy due to the polarization per atom. If dN/dt atoms are circulated then the heat input is

$$\frac{dQ}{dt} = \frac{dN}{dt} \times \frac{(2\mu B)^2}{kT_F} \quad (2)$$

With $dN/dt = N_A \times dn/dt$ where N_A is Avogadro's number, a circulation rate of 30μmoles/second and B=20T, the above equation gives a heat input of 6.7×10^{-7}W.

In the limiting dilute mixture of 6.4% of He^3, the Fermi temperature does not decrease because of the decreased exchange interactions between the He^3 atoms[4]. However, as the He^3 atoms diffuse through the He^4, because of osmotic pressure, the mixture becomes more dilute and thus the polarization will increase. In the dilute case $T_F = 2.6x^{2/3}K$ [5,6] with x denoting the He^3 fraction. As the He^3 diffuses it can reach x=0.01 or lower. If at that point the liquid is in the magnetic field, with x=0.01, T_F=.121K and the heat leak is increased by a factor of 3.

If (1) and (2) are combined, the rate of circulation drops out and one can arrive at a limiting lowest mixing chamber temperature which is given by

$$T_m{}^2 = \frac{N_A(2\mu B)^2}{84kT_F} \tag{3}$$

or, if one inserts the numerical values for the constants

$$T_m = \frac{4.89 \times 10^{-4} B}{T_F{}^{1/2}} \tag{4}$$

here the temperature is in K and B in Tesla.

The above analysis applies to an ideal dilution refrigerator where the incoming concentrated He^3 mixture comes in from the heat exchangers at the temperature of the mixing interface, and there is no external heat leak. Because of these and other effects, the actual lowest temperature of the mixing chamber will be higher than the above estimates. For B=20T, and a limiting mixture of 1% He^3, (4) gives a limiting temperature of 28mK. (1mK=10^{-3}K)

The above sample calculation, is meant to point out that in high magnetic fields the heat input due to the polarization of the He^3 atoms is significant, and in some cases can be the limiting factor in the lowest temperature reached. It might also point towards an alternate design for dilution refrigerators for work in high magnetic fields, where the mixing chamber is in zero field, and the heat is extracted from the sample, which is in the field, by means of a cold finger and heat exchangers.

An alternate design would be one in which only the He^4 circulates[6]. In that case the polarization of He^3 in the field would be constant and there would be no continuous heat input. The initial heat due to the polarization will be removed by the cooling power of the refrigerator. The latter design, although tried by several researchers, has proved much less powerful than that in which He^3 is circulated.

The above considerations also indicate that a significant improvement in the final temperature can be achieved if the dilution refrigerator is operated in the single cycle mode. In this case no new He^3 would be polarized, but the running time of the refrigerator would be limited by the initial amount of concentrated He^3 in the mixing chamber.

REFERENCES

1) O.V. Lounasmaa, "Experimental Principles and Methods Below 1K", Academic Press, New York, 1974, pp.17-58

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5) D.S. Graywall and M.A. Paalanen, Physica 109 & 110B, 1575, 1982

6) P. Das, R. de Bruyn Outboter, and K.W. Taconis, Proc. Ninth Intern. Conf. Low Temp. Phys., Daunt, Edwards, Milford and Yaqub edts. Plenum Press, New York, 1965 p.1253

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