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NUCLEAR MAGNETIC ORDERING

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Résumé.— Après un exposé des concepts et des méthodes utilisés pour la production et l'observation de l'ordre magnétique dans les systèmes de spins nucléaires, nous présentons des résultats préliminaires de diffraction de neutrons sur un état antiferromagnétique nucléaire de l'hydrure de lithium, produit par désaimantation adiabatique dans le référentiel tournant.

Abstract.— After a description of the concepts and methods used for the production and observation of magnetic ordering in systems of nuclear spins, we present preliminary results of neutron diffraction on a nuclear antiferromagnetic state of lithium hydride, produced by adiabatic demagnetization in the rotating frame.

1. PRODUCTION AND OBSERVATION OF NUCLEAR MAGNETIC ORDER.

1.1. Introduction.— The study of nuclear paramagnetism started in late 1945 with the first observation of nuclear magnetic resonance in bulk matter by Purcell, Pound and Torrey at Harvard and Bloch, Packard and Hansen at Stanford. It immediately spread all over the world and thirty three years later it is still going strong. Besides its many other attractions, there is little doubt that the study of nuclear paramagnetism by the methods of magnetic resonance owes much of its success to the beautiful simplicity of its techniques. A magnet, and rf circuit with a generator, and a sample is all that is needed and despite considerable sophistication and complication of the techniques in later years it remains basically very simple.

By contrast the studies of nuclear magnetic ordering, ferromagnetism and antiferromagnetism, undertaken in the laboratory of Nuclear Magnetism at Saclay thirteen years ago, never had so far any competition from elsewhere. Whether a boon or a curse, this monopoly follows at least in part from the fact that to produce and to observe nuclear magnetic ordering is not the easiest thing in the world.

The purpose of the first part of this talk is the following. A new stage has been reached recently with the observation of long range nuclear magnetic order by neutron diffraction and this seems to be a good time to sketch the historical development of ideas and facts that have led to the present situation.

Although over the years there have been several reports at conferences on NMR or Magnetism this is the first time that nuclear magnetic ordering is discussed at a Low Temperature Conference. The concepts and methods of magnetic resonance applied to nuclear magnetic ordering are sufficiently different from those used by the rank and file low temperature physicist to warrant an introduction to the second part of this talk: there recent results will be presented and confronted to the theoretical predictions.

Before going any further it should be specified that two topics are excluded from this survey: the first is the nuclear ordering in solid ³He, which is covered extensively elsewhere, in this Conference.

The second subject is that of compounds where large induced electronic magnetism is responsible for the magnetic behaviour of the nuclei. We call such studies "pseudo-nuclear magnetism" (not to be confused with nuclear pseudo-magnetism to be defined later on). In any case there is an operational distinction between our work and these two topics: a gap of three orders of magnitude in the critical temperatures.

1.2. Production of nuclear magnetic ordering: ADRF and DNP.— The critical temperature \( T_c \) for magnetic ordering of nuclei through their dipolar interactions, is given roughly by \( k_B T_c = \gamma H_L \), where \( H_L \) is the local nuclear magnetic field, of the order of a few gauss, and \( \gamma \) the nuclear gyromagnetic ratio, and it falls into the microkelvin range. The first goal is then the production of such temperatures.
The most direct method for the cooling of nuclear moments is their adiabatic demagnetization from an initial field $H_0$ as high as possible. The final temperature $T_f$ is given in order of magnitude by $T_f = T_0 H_L / H_0^2$. At present, thanks to the progress of dilution refrigerators, and of superconducting solenoids it is possible to produce initial temperatures in the range of a few millikelvins in fields of the order of ten teslas, or more, leading hopefully to final temperatures in the required microkelvin range. Superconducting magnetometers (squids) are available for nuclear magnetic measurements in very low applied fields.

This was not the method we used for the very good reason that at the start of our studies or indeed during the first successful observation of nuclear antiferromagnetism in 1969, we had at our disposal an iron magnet with a maximum field of $2.7 \text{T}$, a $^3\text{He}$ refrigerator with a temperature of $0.3 \text{K}$, and no squid. On the other hand we had good equipment for observing NMR in high fields.

A) A D R F.- The absence of measuring device in very low field made it imperative to be able to achieve the adiabatic nuclear demagnetization while remaining all the time in a high magnetic field. There is no contradiction either in terms since the word demagnetization means reduction of the magnetization, not of the field, or in fact, for such a demagnetization can be easily achieved in practice, using an rf field. The principle of this operation called ADRF (adiabatic demagnetization in the rotating frame) is best understood using the familiar concept of the rotating frame.

The behaviour of a system of nuclear spins in a large dc field $H_0$ and a small nearly resonant rf field of amplitude $H_1$, rotating at a frequency $\omega$ in the neighbourhood of the Larmor frequency $\gamma H_0$ of the spins, in a plane perpendicular to $H_0$, is described most simply in a frame rotating around $H_0$ with the angular velocity $\omega$. In that frame the nuclear spins behave as if they were "seeing" static fields only: a dc field parallel to $H_0$ but of amplitude $\Delta H = H_0 - H$ and a dc field of amplitude $H_1$ at right angle to it.

The dipolar Hamiltonian of the spins which can be written

$$\mathcal{H}_D = \gamma^2 \sum_{i<j} (I_i^z I_j^z - 3(I_i^+ I_j^-)(I_i^- I_j^+))r_{ij}^{-3}$$

(1)
is replaced in the rotating frame by the so called truncated Hamiltonian where all elements of (1) which do not commute with the Zeeman Hamiltonian:

$$\mathcal{H}_D = \frac{1}{2} \gamma^2 \sum_{i<j} ((1-3 \cos^2 \theta_{ij})(I_i^z I_j^- I_j^+ I_i^+) + \gamma H_0 I_i^z)$$

(2)

where $\theta_{ij}$ is the angle of the unit vector $\hat{r}_{ij}$ with the dc field $H_0$. In a crystal the truncated Hamiltonian $\mathcal{H}_D'$ depends on the orientation of the dc field $H_0$ with respect to the crystal axes. The Hamiltonian of the system can then be written:

$$\mathcal{H} = -\gamma H_0 I_z - \gamma H_0 I_x + \mathcal{H}_D'$$

(3)

This is the Hamiltonian of a system of spins in a static field $\Delta H + H_0$, interacting through the truncated Hamiltonian $\mathcal{H}_D'$ of equation (2). It is plausible and has been verified experimentally that applying the rf field for off resonance, then sweeping the frequency (or the dc field) so as to reduce $\Delta H$ to zero, and finally suppressing the rf field itself, leads to a cooling of the dipolar energy $\mathcal{H}_D'$ in a ratio $H_0 / H_L$, comparable to, but somewhat different from, $H_0 / H_L$ (the truncated Hamiltonian $\mathcal{H}_D'$ yields a somewhat different value $H_L$ for the local field). Besides leaving the dipolar interaction cold in high field, and allowing a wealth of Hamiltonians $\mathcal{H}_D'$ by changing the orientation of the field $H_0$ with respect to the crystal axes, the ADRF procedure has yet a third advantage: by choosing at will the initial sign of $\Delta H = (H_0 - \omega)/\gamma$, the effective field before the ADRF, negative as well positive temperatures can be given to the truncated dipolar energy $\mathcal{H}_D'$. This whole procedure of ADRF may appear as a conjuring trick and a question in particular often rises: how can an ordered state of nuclear spins, where the local ordering fields are of the order of a few gauss at most, survive in the presence of a dc field $H_0$ of several teslas? The answer is that as soon as the rf field is cut off there is no way for the Zeeman energy which is quantized in units of hundreds of megahertz to flow into the dipolar energy whose spread is at most a few tens of kilohertz per spin.

B) D N F.- The adiabatic demagnetization provides a cooling ratio of three to four orders of magnitude. However even if fields of ten teslas and lattice temperatures of a few millikelvins are available,
there is still a problem for reaching the final microkelvin range. At least in insulators the nuclear spin-lattice relaxation times at such fields and temperatures, (and even for fields lower by a factor three and temperatures higher by a factor ten) are so long that the nuclear spins never reach the temperature of the refrigerator (you can take the horse to the water but you cannot make it drink). The situation is better in metals but one would expect there difficulties with the ADRF. There exists however a method of dynamic nuclear polarization (DNP), widely used in the making of polarized targets for nuclear and particle physics, which can bring nuclear spins to temperatures of a few milikelvins in fields of a tesla in a few hours.

The principle of this method, originally called the "solid effect" has been described in many different ways. The description given here, should appeal, one hopes, to low temperature physicists.

Paramagnetic electronic impurities are introduced into an otherwise diamagnetic sample at concentrations of the order of \(10^{-4}\) (within an order of magnitude) and because of the short electronic spin-lattice time have no difficulty in reaching the temperature of the lattice (and of the refrigerator) which is of the order of half a kelvin or so. The electronic spins interact with each other through a truncated electronic dipolar interaction \(\mathbf{H}_D^e\) which corresponds to an internal electronic magnetic field \(H_L^e\) of the order of say twenty gauss. Actually this concept of local electronic field for a randomly dilute system of spins should be used with caution. For most pairs of electronic spins it will be much less and for a few it would be a good deal more. The main point is that because of the large electronic gyromagnetic factor \(\gamma^e\), the spread of the energy spectrum of \(\mathbf{H}_D^e\), of the order of \(\gamma^e H_L^e/2\pi = 50\) MHz will have wings reaching into the nuclear Larmor frequency of the order of a hundred MHz. The nuclear Zeeman energy \(Z_n\) and the electronic truncated dipolar energy \(H_D^e\) are thus "on speaking terms" and at the same spin temperature.

If now we perform an ADRF on the electronic spins with a microwave generator near the electronic Larmor frequency which is in the range of a hundred GHz, we should cool the electronic dipolar energy by a factor of the order of \(H_L^e/\gamma^e\) that is three orders of magnitude. Since \(H_D^e\) and \(Z_n\) are on "speaking terms" this results in a cooling of the nuclear Zeeman energy \(Z_n\) but by a far smaller amount because of the heat capacity of \(Z_n\), much higher than that of \(H_D^e\). However once the ADRF is over, because of the short electronic relaxation time, one can repeat it again and again until \(Z_n\) has reached a temperature smaller than that of the lattice by a factor of the order of \(H_L^e/\gamma^e\) that is reaching into the milikelvin range. In practice, instead of repeating the electronic ADRF many times one obtains a comparable result by applying the microwave field continuously at a distance from the electronic resonance of the order of \(H_L^e\). Depending on the side of the resonance at which this microwave is applied, temperatures of either sign are obtained for \(Z_n\). Cutting off the microwave field one is then ready for a nuclear ADRF which brings the nuclear dipolar temperature down into the microkelvin range. The lifetime of the ordered nuclear state which obtains if the final temperature is below the critical temperature \(T_c\) of the order of the spin-lattice relaxation time \(T_{1D}\) for the nuclear dipolar energy. This time is very much shorter than the relaxation time \(T_{1L}\) for the nuclear Zeeman energy \(Z_n\) because at low lattice temperatures the spectrum of the fluctuating magnetic local fields responsible for the nuclear relaxation does not contain the high (100 MHz) nuclear Larmor frequency, whereas it does contain the low frequencies spanned by the spectrum of the nuclear dipolar energy. In practice relaxation times \(T_{1D}\) between a few minutes and a few hours have been obtained.

1.3. Observation of nuclear magnetic ordering.— Like electronic magnetic ordering it involves three types of measurements.

A) Macroscopic magnetic measurements.— What is meant here is the use of magnetic fields homogeneous on a scale comparable to the size of the sample. Whereas in electronic magnetism these fields are mostly static, in high field nuclear ferro or antiferromagnetism these are rf fields near the Larmor frequency of the nuclei. The NMR signal of an ADRF state whether paramagnetic or ordered has zero net magnetization and therefore zero net area. It can be shown quite generally that it is antisymmetrical with respect to the nuclear Larmor frequency. Two such signals of \(^7\)Li in LiH are shown in figure 1. The first corresponds to an antiferromagnetic state and the second to a paramagnetic state. The first one is easy to interpret : nuclear moments located on the two antiferromagnetic sublattices have diffe-
rent Larmor frequencies because they see opposite Weiss fields. Those parallel to the high field \( H_o \) absorb energy from the NMR field and given an absorption signal, those, on the other sublattice, antiparallel to \( H_o \) give an emission signal of opposite sign. The lower the spin temperature, the higher, the narrower and the farther apart are the two peaks.

In the paramagnetic ADRF state there is no long-range order one still sees two peaks of opposite sign. This is explained by short range correlations between the spins and therefore also between the orientation of a spin and that of the local field produced by its neighbours. Moments which are parallel to \( H_o \) and give a positive signal see local fields opposite in sign to those seen by moments antiparallel to \( H_o \), whence the antisymmetrical structure with two peaks of opposite sign. It is clear that from the looks of an ADRF signal it is difficult to tell apart an antiferromagnetic state slightly below the transition from a paramagnetic state slightly above.

It is possible however to extract from the ADRF NMR curve \( f(\omega) \) significant quantitative information. It can be shown that the first moment \( M_1 \) of \( f(\omega) \) with respect to the central frequency \( \omega_0 \) is proportional to the dipolar energy of the spins if there is a single spin species I present in the sample:

\[
M_1 = \int_{-\infty}^{\infty} (\omega - \omega_0) f(\omega) \, d\omega = \frac{\mathcal{J}_0}{\pi}
\]

(4)

If there are two spin species I and S the significance of the first moment \( M_1 \) is more involved. It can be shown that

\[
M_1 = \left\{ 3 \left< \mathcal{J}_{II} \right> + 2 \left< \mathcal{J}_{IS} \right> \right\}
\]

where \( \mathcal{J}_{IS} \) is the dipolar interaction between the spins I and S.

Another quantity of great importance is the transverse static susceptibility of the nuclear spins which is given by the relation:

\[
\chi_\perp = \zeta \int_{-\infty}^{\infty} \frac{f(\omega)}{\omega - \omega_0} \, d\omega
\]

It is well known that for an antiferromagnet the transverse susceptibility is very nearly independent of the temperature.

There is no simple way of measuring the temperature in the ADRF state, the relation

\[
T / T_F = \frac{H_o}{H_L}
\]

being only a crude approximation. On the other hand the entropy is known in principle: if the ADRF is truly adiabatic, it is the same as before the demagnetization where it is a simple function of the initial nuclear polarization \( p_i \), going from \( k_B \ln (2I+1) \) to zero as the polarization goes from zero to unity. Figure 2 shows a plot of \( \chi_\perp \) against \( p_i \) for \( ^{19}\text{F} \). The plateau characteristic of antiferromagnetism is unmistakable but the transition polarization not so easy to pinpoint.

B) Nuclear probes. - In electric antiferromagnetism the use of nuclear moments as probes which measure on a microscopic scale the local magnetic fields at various lattice sites has proven very fruitful. The same technique has been successfully applied to the study of nuclear antiferromagnetism. These studies have been reported before and will be mentioned here very briefly. The most spectacular success of this method is the discrimination between two states of the spins of \( ^{19}\text{F} \) in \( \text{CaF}_2 \), antiferromagnetism and domain ferromagnetism, which can both

Fig. 1: NMR signal of \( ^7\text{Li} \) in \( \text{LiH} \) after ADRF at \( T < 0 \) with \( H_o \) parallel to \{100]\:
A : Antiferromagnetic state
B : Paramagnetic state

\( ^7\text{Li} \) NMR Signal
be produced in Ca F₂ for different orientations of the magnetic field. Whereas the ADRF NMR signals of "F look practically identical in both states, the NMR signals of the rare (0.13 %) isotope of "Ca give a single resonance line for antiferromagnetism and two separate lines for ferromagnetism. Similarly the existence of antiferromagnetism in LiH was first demonstrated unambiguously from a splitting in the signal of the rare isotope ⁶Li.

![Graph](image)

**Fig. 2:** Transverse susceptibility of "F in CaF₂ after ADRF at T < 0 with H₀ parallel to [100] as a function of the initial polarization. The plateau is as expected for an antiferromagnet.

One of the weaknesses of the method is that in contrast with electronic antiferromagnetism the nuclear probes do perturb the magnetic environment they are set to study. This is not offset by their small concentration: even if they perturb only small regions of the sample, it is these very regions that are observed.

C) Neutron diffraction.—As in electronic magnetism this is the method which brings the most detailed information by far. It will be dealt with in detail in the second part of this talk. One should at this stage warn the reader against undue pessimism: in spite of the fact that nuclear magnetic moments are three or four orders of magnitude smaller than the electronic moments, neutron diffraction by nuclear spins is not a weak phenomenon. This is due to the fact that besides magnetic interactions there are sizeable nuclear interactions between the spin of the nucleus and that of the neutron which enable the neutron to "tell" a nuclear spin up from a nuclear spin down. The order of magnitude of these interactions is described conveniently by assigning to each nuclear species a hypothetical pseudo-magnetic moment \( \mu^* \) which would provide a magnetic scattering amplitude equal to the actual nuclear spin-dependent scattering amplitude, of that nucleus. The pseudo-magnetic moments of most nuclei were very poorly known and original methods, for measuring these moments have been developed at Saclay. The general name of nuclear pseudomagnetism has been proposed for these studies. It was a great disappointment that \( \mu^* ({}^{19}\text{F}) \) has turned out to be very small (0.017 \( \mu_B \)). Otherwise neutron diffraction studies of nuclear antiferromagnetism would have been reported at least five years earlier.

1.4. Landmarks in nuclear magnetic ordering.—
1958 - Discovery of DNP by the solid effect /1/
1960 - Proposal for observing nuclear ordering using DNP followed by adiabatic demagnetization /2/
1962 - Proposal for using DNP followed by ADRF /3/
1965 - Experimental work on nuclear ordering starts (M. Chapellier and M. Goldman)
1968 - Prediction of ordered nuclear structures /4/
1969 - First observation of nuclear antiferromagnetism in Ca F₂ /5/
1972 - First measurements of pseudo-magnetic moments /6,7/
1971/1974 - Experimental work on LiF (Bouffard and Cox) /10/
1974 - First use of nuclear probes and first observation of nuclear domain ferromagnetism in Ca F₂ /8,9/
1974 - Experimental work starts on LiH (Bouffard and Roinel)
1977 - First observation of nuclear antiferromagnetism in LiH /11/
1978 - First superstructure Bragg diffraction in LiH /12/

2. NEUTRON DIFFRACTION STUDY OF ANTIFERROMAGNETISM IN LITHIUM HYDRIDE.—The possibility of performing a neutron diffraction study on a nuclear antiferromagnet is limited to substances whose nuclei have a sufficiently large pseudo-magnetic moment \( \mu^* \). Furthermore, for a first study it is advisable to choose a system as simple as possible where the prediction of antiferromagnetism has a good chance to be correct. These considerations have led to the choice of lithium hydride: The pseudomagnetic moment of the proton is the largest of all nuclei, \( \mu^* ({}^1\text{H}) = 5.4 \mu_B \), and that of lithium 7 is \( \mu^* ({}^7\text{Li}) = - 0.62 \mu_B \). As for the crystalline structure of LiH, it is of the Na Cl type, i.e. it co-
sists of two imbricated f.c.c. lattices of $^1\text{H}$ and $^7\text{Li}$. If one disregards for a moment the difference between $^1\text{H}$ and $^7\text{Li}$, they form together a simple cubic lattice of magnetic moments of comparable magnitude (they differ by about 15\%), for which it is plausible to expect the same ordered structures as in a s.c. lattice of identical spins. The successful production of nuclear antiferromagnetism as deduced from magnetic measurements, in \text{CaF}_2 whose $^{19}\text{F}$ spins form a s.c. structure was an incentive to trust the theoretical predictions for antiferromagnetism in LiH.

The successful observation of neutron diffraction on antiferromagnetic lithium hydride is very recent, and the results presented in this talk are still very preliminary.

2.1. Predicted antiferromagnetic structures.- The theoretical prediction of the ordered structures is made by a local mean field approximation. Figure 3 shows the antiferromagnetic structures expected both at positive and negative spin temperatures when the external field is parallel to a four-fold crystalline axis. This is the field orientation to which the neutron diffraction study has been limited so far. At positive temperature successive planes (011) carry opposite magnetizations, and at negative temperature it is successive planes (100) that carry opposite magnetizations. Each of the antiferromagnetic sublattices contains spins of either species.

The experimental arrangement, described in the next section, is such that the neutron diffraction must take place in a plane perpendicular to the field \( H_0 \) that is on antiferromagnetic planes parallel to \( H_0 \). Since the neutrons "see" essentially the protons, it is possible to perform an antiferromagnetic diffraction on the planes (011) both at positive and negative temperature (dashed planes in figure 3). One way to distinguish the two structures of figure 3 is that in a given (011) plane the proton and lithium polarizations are parallel at \( T > 0 \) and anti-parallel at \( T < 0 \); these polarizations are reversed from one plane to the next.

2.2. Experimental procedure.- The whole experimental procedure: dynamic polarization and ADRF has to be performed in a high homogeneous field and at low temperature, that is in a superconducting magnet and with a dilution refrigerator. At the same time, free access must be provided to the incident and diffracted neutron beams: an unacceptable absorption would result from their crossing the coil or an excessive thickness of dilute $^3\text{He}$.

The superconducting magnet is of the split-coil type, which allows neutron-diffraction experiments in a plane perpendicular to the (vertical) magnetic field. The sample of LiH, in the form of a platelet of typical dimensions $5 \times 4 \times 0.5 \text{ mm}$ is placed vertically in the cryostat. The thickness of the $6\% - ^3\text{He}$ solution is limited to 0.5 mm on each crystal face, as a compromise between the necessities of cooling the crystal and reducing neutron absorption. The whole cryostat can be rotated around a vertical axis, so as to bring the crystal to the Bragg-reflexion orientation.

The cryogenic system, and the neutron-diffraction setup are described in separate papers at this conference.

The lithium hydride sample contains of the order of $2 \times 10^{19}$ paramagnetic F-centres per cm$^3$. They are created by irradiation at liquid nitrogen temperature with a beam of 3-MeV electrons. The magnetic field is 6.5 teslas, and the frequency of the microwave irradiation used for DNP is 185 GHz. During the polarization period, the temperature of the bath is around 200 mK. The maximum polarization, after 2 to 3 days of irradiation, corresponds to:

\[ P_H = 95\% \; ; \; P_{^7\text{Li}} = 80\% . \]

After switching-off the microwave power, the bath temperature drops to 35 mK. The temperature of the sample itself is not known. The ADRF is performed on both $^1\text{H}$ and $^7\text{Li}$ spins, by using two rf fields of carefully adjusted frequencies, (of the order of 280 and 110 MHz, respectively). The rf-field amplitudes are of the order of 30 mG, and the external...
field is swept towards resonance at rate of 0.5 G/s.

2.3. Experimental results.- We report some experimental results obtained on one sample at negative spin temperature. The field is along a four-fold crystalline axis to within a fraction of a degree, as deduced from the observation of the crystalline neutron-diffraction reflexions 200 and 220.

Figure 4 shows the antiferromagnetic diffraction line 110 observed immediately after an ADRF with initial polarizations $p_H = 0.95$ and $p_{Li} = 0.80$. On the same figure is shown for comparison the crystalline diffraction line 220 observed with the unpolarized sample. The reality of a long-range nuclear antiferromagnetic order whose structure is precisely that expected from theory, is thus directly established. The diffraction of neutrons by this nuclear antiferromagnet is a large effect, as anticipated from the large value of the proton pseudomagnetic moment. The width at half-intensity of the antiferromagnetic line, equal to 0.65°, is much larger than that of the crystalline line 220 (≈ 0.2°).

It is experimentally the same whatever the initial polarizations and the antiferromagnetic line intensity. This broadening is attributed to the existence of antiferromagnetic domains, and it yields an average value for their size, of the order of 300 Å.

Fig. 5: Variation with time of the neutron counting rate at the centre of the antiferromagnetic line observed in one run. It consists of a fast decay, completed in about 4 h, superimposed on a slow decay which lasts 5 h. Further experiments have shown that this is due to an inhomogeneous relaxation rate in the sample, whose origin and nature have not been investigated yet. This relaxation leads to a distribution of spin temperatures within the sample which becomes broader and broader as time proceeds. The methods used to overcome this drawback is to perform, after each ADRF, a series of partial saturations of the system, homogeneous over the sample, in a time much shorter than the shortest relaxation time. These saturations are performed by suitable rf irradiations. Following each saturation step the system has a relatively homogeneous spin temperature, whose value increases at each step.

![Figure 4: Neutron diffraction lines in LiH. The crystalline line 220 is observed in the unpolarized sample. The antiferromagnetic line 110 is observed after ADRF at $T < 0$ and $H_o // [100]$](image)

What is measured at the various saturation steps of each run is the intensity of the 110 antiferromagnetic neutron line in LiH. Before the end of the ADRF, the neutron count is that of the background (left).
The result of this analysis of the data is shown in figure 6. The point A corresponds to the zero temperature limit in the Weiss-field approximation.

\[
E' = (3 \left< \chi_{iS}^{2} \right> + \left< \chi_{jS} \right>) / N_S
\]

The qualitative observations accumulated on nuclear magnetic ordering: magnetic measurements and neutron diffraction, demonstrate unambiguously that the steady state reached by an isolated system of nuclear spins is a true thermodynamic equilibrium, with a true temperature in a range several orders of magnitude below those achieved in any other macroscopic system.

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