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**High Energy Physics  
with Polarized Beams  
and Polarized Targets**  
(Argonne, 1978)

Editor  
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## FOREWORD

This year is in some sense a milestone in polarization physics. The polarized beam facility at Argonne will be closing down, along with the ZGS, and one has the chance to evaluate the output from that program. Moreover, polarized beams and targets have been used in lepton interactions and these results indicate the great potential of studying the spin dependence of fundamental interactions. Finally, it is now apparent that the techniques used at the ZGS for making a polarized beam can be extended to strong focusing machines. Therefore, the general physics community has an interest in determining whether such technology can be used to answer questions of fundamental interest.

These considerations played a role in the organization of the polarization symposium held in October 1978 at Argonne. We hope these proceedings of that symposium carry some of the flavor of the numerous contributed papers, invited talks and general summary talks which were given. An attempt was made to make the conference truly international, and this can be seen reflected in the number of foreign speakers and participants. It is the hope of the organizing committee that the tradition of this symposium will continue; the plans are to have the next one in Lausanne, Switzerland in 1980.

I would like to take this opportunity to express my gratitude to the many people who have contributed to the organization of the symposium. First to the organizing committee of O. Chamberlain, E. D. Courant, G. Fidecaro, J. D. Jackson, L. Michel, L. Soloviev, S. Suwa, G. A. Voss and their energetic chairman A. D. Krisch for providing general guidance and help in establishing the overall balance of the symposium. In working out the detailed program, I was fortunate to have the suggestions and help of a hard-working Program Committee consisting of R. N. Cahn, D. G. Crabb, H. E. Miettinen, and C. K. Sinclair. The conference secretary K. Novak performed an outstanding job in taking care of correspondence and the several mailings which were made prior to the symposium. I would also like to especially thank her, as well as M. Ambats, B. Angelos and J. Day for their help as conference secretariat. Without their vigilance, the symposium could not have gone as smoothly. Also, we are indebted to the professional services of the Conference Planning and Management Staff, M. Holden and D. Burdzinski, for their logistical help at all stages of the symposium.

To the speakers I am grateful, for they are responsible for the scientific excellence of the program. They are to be especially thanked for producing a written record of their talks for these proceedings. The session chairman should also be commended for accomplishing the difficult task of keeping physicists from talking too long.

My final thanks go to Argonne, AUA, The University of Chicago, The University of Michigan, and The ZGS Users group who provided special funding for the symposium. On behalf of all the participants we are especially appreciative to the AUA for the lovely meal in the Sullivan Room of the Chicago Art Institute, and the special tour of the Pompeii exhibit which followed.

G. Thomas  
Argonne National Laboratory  
February, 1979

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## POLARIZED TARGETS IN HIGH ENERGY AND ELSEWHERE

A. Abragam

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The subject of polarized targets had been covered extensively in two international conferences that took place at Saclay in 1965 and Berkeley in 1971. Proceedings have been published for both.

One of my problems as an invited speaker at the present Conference is to avoid repeating what I have said at the previous two. This goal is best achieved by speaking of things that happened long before the first, or after the second.

With respect to the latter period there is a second problem : namely that I have no first-hand knowledge of what happened, in the field of polarized targets for High Energy Physics since 1971. This is why the second part of this talk will be dealing with "elsewhere".

## The Overhauser Effect

To come back to the first part we go back to 1953 and to Overhauser's proposal to polarize nuclei in metals by saturating the ESR resonance of conduction electrons.

This proposal presented at a meeting of the APS did not meet, to say the least, with unanimous approval. For a suitable description of the reactions of the audience I would like to borrow that given to me a long time ago by the late Van de Graaf à propos of the PhD thesis examination of Louis de Broglie, that he had attended in Paris in 1923, an historical event.

"Never has so much gone over the heads of so many".

In spite of the general incredulity two brave men, T.R.Carver and C.P.Slichter decided to do just what Dr Overhauser had ordered, saturate the ESR of conduction electrons of sodium metal and see what happens. What happened is shown in Fig.1, an NMR signal of  $^7\text{Li}$ , quite invisible in the absence of electron saturation. Overhauser had also predicted that the ESR line should be displaced by the field produced by the polarized nuclei and "seen" by the conduction electrons. This is shown in Fig.2 (Saclay 1960), where the ESR line so displaced, floats back (Overhauser had said snaps back, an overstatement), with a time constant equal to the nuclear relaxation time.

To predict his results Overhauser had made three unnecessarily restrictive assumptions

- a) Fermi statistics for the conduction electrons
- b) Equal number of electrons and nuclei
- c) A scalar coupling of the form  $a\mathbf{I}\cdot\mathbf{s}$  between electronic and nuclear spins.



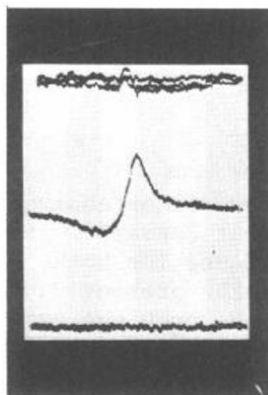


Fig.1 - Enhanced signal of  $^7\text{Li}$  in lithium metal.

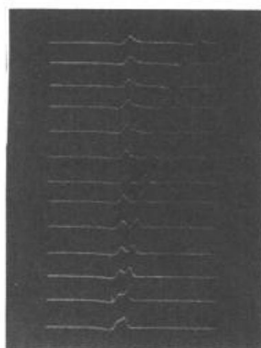


Fig.2 - Displaced ESR line in lithium metal.

It was rapidly realized that neither of these three assumptions was necessary. Fig.3 shows a large Overhauser enhancement of the NMR signal of  $^{29}\text{Si}$  (Saclay 1958), observed in semi-conducting silicon where conduction electrons are far less numerous than the nuclei of  $^{29}\text{Si}$  and are known to obey Boltzmann statistics, in contradiction with assumptions a) and b).

Fig.4 (Saclay 1958) shows Overhauser enhancement of nuclear signals of protons in water where dissolved free radicals with unpaired electronic spins play the part of conduction electrons. The electron-nuclear coupling is known to be dipolar rather than scalar. In a paper published in 1955 under the title "The Overhauser effect in non-metals" I had shown that dipolar electron-nucleus coupling led to an Overhauser nuclear polarization enhancement of a sign opposite to that predicted for a scalar coupling, in agreement with Fig.4.

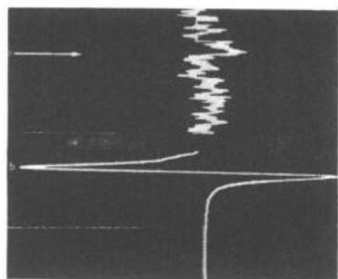


Fig.3 - Enhanced signal of  $^{29}\text{Si}$  in semi-conducting silicon.

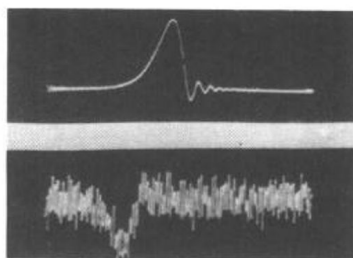


Fig.4 - Enhanced signal of protons in water containing free radicals.

In lectures, although never in print, and to call attention to the negative sign of the enhancement I had referred to it as the Underhauser effect. This had the unfortunate consequence of misleading a very respectable colleague who later wrote a large textbook on magnetic resonance where Underhauser appears in the Name Index.

After disbelieving Overhauser's predictions until Carver and Slichter proved dramatically their validity, there was a swing in the opposite direction, a widespread belief that the saturation of an ESR resonance in any type of bulk matter should lead to an enhanced nuclear polarization.

### The Solid Effect

In my paper of 1955 I had analyzed the situation in solid insulators and shown that saturation of an ESR resonance due to fixed paramagnetic impurities with dipolar coupling to surrounding nuclei should *not* lead to an Overhauser enhancement. It was three years later in 1958 that it occurred to me (and quite independently to Carson Jeffries at Berkeley) that, in that case, driving the forbidden transitions, sum or difference of electronic and nuclear frequencies, could lead to a large nuclear polarization parallel or antiparallel to that of the electrons.

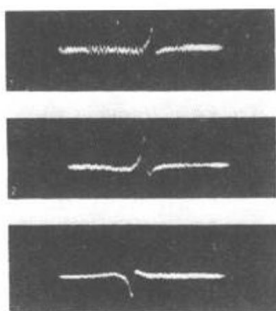
Fig.5 (Saclay 1958) shows how this phenomenon occurs in LiF where the rare isotope  ${}^6\text{Li}$  with a small magnetic moment plays the part of the nucleus and the large moment of  ${}^{19}\text{F}$  that of the electron. Driving the frequency  $\Omega = \omega({}^{19}\text{F}) \pm \omega({}^6\text{Li})$  yields for  ${}^6\text{Li}$  a polarization enhanced by  $\mp \gamma({}^{19}\text{F})/\gamma({}^6\text{Li}) \approx \mp 6$ .

I cannot understand why it took me, (or anybody else who took the trouble to read the paper), three long years to discover something which was really implicit in my analysis of 1955 but there it is.

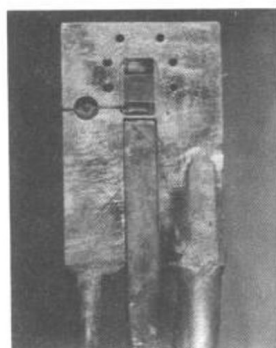
In magnetic resonance there is a fundamental difference with far-reaching consequences between solids where the relative positions of the spins are fixed and liquids where they move rapidly with respect to each other. To distinguish the Overhauser effect where, be it in metals, semiconductors, or liquids, electronic and nuclear spins move rapidly with respect to each other, from the new effect where the relative positions of electronic and nuclear spins are fixed I had called the new effect the "solid effect".

### Polarized Targets

The discovery of the "solid effect" started research on "dynamic nuclear polarization" and then on polarized targets in various laboratories with Saclay and Berkeley being by far the most active in the field.

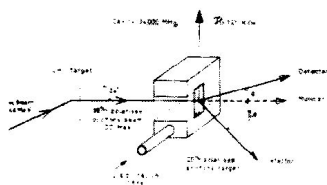


**Fig.5** - Enhanced signal of  ${}^6\text{Li}$  obtained by "solid effect" in LiF.



**Fig.6** - Thin target of LMN for low energy protons.

The first experiment using a polarized proton target and a low energy polarized proton beam was performed at Saclay in 1962. The first high energy experiment with a polarized target and a high energy pion beam, or at least what at the time was considered as a high energy beam, was performed at Berkeley in 1963. Fig. 6,7,8, of historical interest now, show some details of the first Saclay experiment, the target, a thin crystal of LMN (short for Lanthanum Magnesium Nitrate) doped with cerium, the lay-out of the experiment and a photograph of the target assembly.

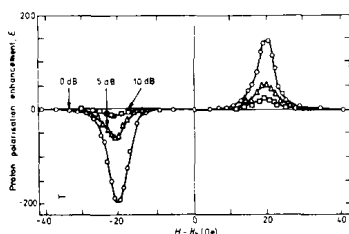


**Fig.7** - Scattering of low energy protons by a polarized LMN target experimental lay-out. a)



**Fig.8** - Scattering of low energy protons by a polarized LMN target experimental lay-out. b)

In my talk at the Saclay conference of 1965 I had given a simple-minded description of the well resolved solid effect as resulting from forced flips-flops or flip-flips of an electron-nucleus pair followed by a relaxation back flip of an electron-spin. This model describes well the situation in a substance such as LMN in high field, doped with neodymium, where the electronic line width is much smaller than the nuclear Larmor frequency. This is illustrated in Fig.9 which shows that enhancements of opposite sign of the nuclear polarization do indeed occur for microwave frequencies  $\Omega = \omega_e \pm \omega_n$ . For several years, say from 1962 to 1966, LMN was the main proton-target material.



**Fig.9** - Enhancement of proton NMR signal in LMN by solid effect.

Its main attractions were the ease with which single crystals could be grown and above all the high proton polarizations, 70 % or more, that it yielded.

Its main defect was the small ratio of free polarized protons to all the protons of the target, of the order of  $f \approx 0.06$  and there was a growing demand from high energy physicists, for target materials with higher free protons content.

The most obvious choice solid orthohydrogen  $H_2$ , did not work because of the strong leakage relaxation of the protons due to their intramolecular coupling. Such a coupling is not effective in its ground state  $J = 0$  in ortho hydrogen free solid HD, which for that reason looked more promising, and was studied at Saclay for over a year to no avail. The snag was the very long electronic relaxation time of the electronic centres, namely hydrogen (and deuterium) atoms produced by irradiation of the sample with  $\gamma$  rays.

More modestly, the solution chosen in the late sixties was organic substances, alcohols (butanol) doped with free-radicals (porphyrinoids), and diols (propanediol) doped with  $Cr^{VI}$  complexes, which provided ratios  $f$  of the order of 0.24 for butanol and 0.19 for pro-

panediol.

On the experimental side a great step forward was the move to lower temperatures with the use of  $^3\text{He}$  cryostats and later on of dilution refrigerators.

At present proton-polarizations nearing 100 % are obtained for instance in propane-diol doped with  $\text{Cr}^{\text{V}}$ .

### Spin Temperature Theory of DNP

The process of dynamic polarization in these substances is somewhat different from the simple scheme of the well-resolved solid effect and cannot be understood without introducing the concept of spin-temperature. I am going to give of that process a description somewhat different from that given usually, because I shall make use of it in the second part of my talk. It was well accepted some time ago by low temperature physicists ; whether it agrees with particle physicists remains to be seen. The description is in three steps :

#### a) Adiabatic demagnetization

It has been known for many years that a system of interacting magnetic moments in thermal equilibrium in a high magnetic field  $H_0$  could be cooled efficiently by adiabatic demagnetization. Reducing the applied field from the initial value  $H_0$  to zero, results in a temperature reduction  $T_i/T_f$  of the order of  $H_0/H_L$  where the constant  $H_L$ , much smaller than  $H_0$ , is a measure of the local field, "seen" by a given moment and produced by its neighbours.

#### b) Adiabatic demagnetization in high field

Given a system of interacting spins in high field it is also possible to achieve their adiabatic 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 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  $\Delta H = H_0 - \omega/\gamma$  and a dc field of amplitude  $H_1$  at right angle to it.

The dipolar Hamiltonian of the spins which can be written

$$H_D = \gamma^2 \hbar^2 \sum_{i < j} \{ \vec{I}_i \cdot \vec{I}_j - 3(\hat{r}_{ij} \cdot \vec{I}_i)(\hat{r}_{ij} \cdot \vec{I}_j) \} r_{ij}^{-3} \quad (1)$$

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 :

$-\gamma\hbar H_0 \cdot \tilde{I} = -\gamma\hbar H_0 I_z$  are thrown out :

$$H'_D = \frac{1}{2} \gamma^2 \hbar^2 \sum_{i < j} (1 - 3 \cos^2 \theta_{ij}) \{3 I_{iz} I_{jz} - I_i \cdot I_j\} r_{ij}^{-3} \quad (2)$$

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  $H'_D$  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 :

$$H = -\gamma\hbar \Delta H I_z - \gamma\hbar H_1 I_x + H'_D \quad (3)$$

This is the Hamiltonian of a system of spins in a static field  $\Delta H \hat{z} + H_1 \hat{x}$ , interacting through the truncated Hamiltonian  $H'_D$  of eq. (2). It is plausible and has been verified experimentally that applying the rf field far 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  $H'_D$  in a ratio  $H_0/H_L$ , comparable to, but somewhat different from,  $H_0/H_L$ , (the truncated Hamiltonian  $H'_D$  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  $H'_D$  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  $H'_D$ . Once the ADRF is over, the rf field  $H_1$  can be suppressed.

### c) DNP

Paramagnetic electronic impurities introduced in the sample, because of their short spin-lattice relaxation time, have no difficulty in reaching the temperature of the lattice (and of the refrigerator) which is of the order of a kelvin or so. The electronic spins interact with each other through a truncated electronic dipolar interaction  $H'^e_D$  which corresponds to an internal electronic magnetic field  $H^e_L$  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  $H'^e_D$ , of the order of  $\gamma_e H^e_L / 2\pi \approx 50 \text{ MHz}$  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  $H'^e_D$  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  $H_0/H^e_L$  that is three orders of magnitude. Since  $H'^e_D$  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  $H_0/H_L^e$  that is reaching into the millikelvin 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  $Z_n$ .

Thus it is literally a cooling of nuclear spins that occurs in the DNP process. This is exemplified by the fact that if there is more than one nuclear species in the sample with different magnetic moments and or spins, they reach the same nuclear spin temperature  $T_S$  rather than the same polarization. The different nuclear polarizations resulting from this common spin temperature are easily computed by the classical formulae  $P = B_I(\gamma_I H_0/k_B T_S)$  where  $B_I$  is the well-known Brillouin function for spin  $I$ . Fig.10 shows the inverse temperatures reached by proton and deuteron spins in a substance containing both, plotted against time (CERN 1974). The fact that proton and deuteron points fall on a single smooth curve is convincing evidence of the existence of a single nuclear spin temperature.

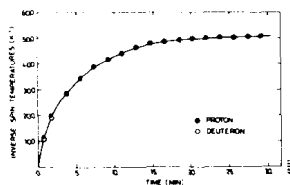


Fig.10 - Growth of inverse spin temperature for protons and deuterons during dynamic polarization.

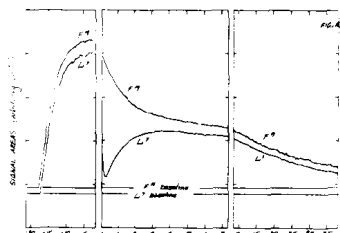


Fig.11 - Thermal coupling of  ${}^7\text{Li}$  and  ${}^{19}\text{F}$  in dynamic polarization.

In Fig.11 (Saclay 1973) the following experiment was performed in dynamically polarized LiF. The polarization of  ${}^7\text{Li}$  is suddenly reduced by a strong rf field. Its polarization then grows at the expense of the  ${}^{19}\text{F}$  polarization at a rate which expresses the coupling between the two nuclear species. Neither one is directly on "speaking terms" with the other because of their widely different Larmor frequencies but they communicate indirectly through the electronic spin-spin energy. Having thus reached the same spin temperatu-

re, both species relax together at a much slower rate towards the lattice temperature.

The existence of a common spin temperature explains why in a sample where the proton polarization is within experimental error 100 %, the deuteron polarization does not exceed 45 %. This follows directly from the fact that  $\gamma(D) \ll \gamma(^1H)$ .

We pass onto the second part of this talk, "polarized targets elsewhere".

### Nuclear Antiferromagnetism and Neutron Diffraction

It is well known that interacting magnetic moments can order themselves below a certain critical temperature  $T_c$  to form a new phase. The long range arrangement of moments in this ordered phase can be ferromagnetic, antiferromagnetic or even more complicated.

For the last 25 years the study of electronic antiferromagnetism has been dominated by neutron diffraction. An antiferromagnetic structure contains successive lattice planes with opposite magnetizations. Thanks to its own magnetic moment a neutron can "tell" a magnetic moment up from a moment down. It will "see" two successive lattice planes in an antiferromagnetic structure as different and the magnetic period of the lattice as twice that of the crystal.

Neutron diffraction can then give rise to extra Bragg reflections at an angle different from that for the normal lattice.

These extra Bragg lines, called superstructure lines or antiferromagnetic lines appear below the critical temperature.

We had set as our goals at Saclay a) the production of antiferromagnetic structures of nuclear spins originating in their mutual dipolar interactions b) the observation of antiferromagnetic Bragg peaks.

Both goals appear at first sight as rather formidable.

#### a) Production of nuclear antiferromagnetism

The critical temperature  $T_c$  for a nuclear antiferromagnetic transition is given in order of magnitude by  $k_B T_c \sim \mu H_L$  where  $H_L$  is the nuclear local field and  $\mu H_L$  is the magnetic energy of a nuclear magnetic moment  $\mu$  in that field. By taking for  $H_L$  a few gauss, which is the right order of magnitude for a system of nuclear spins and for  $\mu$  the magnetic moment of, say, a proton a temperature  $T_c$  of a microkelvin is obtained. It may be amusing for high energy physicists to remark that if one takes as a central energy 10 eV, average ionization energy of an atom,  $\mu H_L \approx 10^{-10}$  eV, is as far below it, as one TeV, energy planned in the Fermilab energy doubler, is above.

Such temperatures can in fact be obtained in a straightforward manner using DNP. As explained earlier, the dynamic polarization reduces the temperature of the nuclear Zeeman energy by a factor of the order of  $H_0/H_L^e$ , that is, something like three orders of magnitude. A second reduction of similar magnitude is then obtained by the demagnetization of the nuclear spins themselves. If the lattice temperature is a fraction of a Kelvin, this yields a final dipolar spin temperature in the desired microkelvin range.

The first nuclear antiferromagnetic structure was produced and observed (although not by neutron diffraction for reasons to appear



shortly) 9 years ago at Saclay in a crystal of  $\text{CaF}_2$  where the nuclei of  $^{19}\text{F}$  form a simple cubic lattice.

#### b) Observation by neutron diffraction

One might fear that because the nuclear magnetic moments are three to four orders of magnitude smaller than electronic moments, neutron diffraction by an antiferromagnetic nuclear structure would be a very weak phenomenon. This is not so.

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 pseudomagnetic 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.

#### 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 pseudomagnetic 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  $\text{LiH}$ , it is of the  $\text{NaCl}$  type, i.e. it consists of two intercalated f.c.c. lattices of  $^1\text{H}$  and  $^7\text{Li}$ .

Fig.12 shows the antiferromagnetic structure expected at negative spin temperature 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.

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  $^3\text{He}$ .