sorption site. Both of these are difficult to determine accurately in SEXAFS. For the angle-resolved UPS modulations discussed here, the emissions are measured at fixed final directions $\vec{k}_f$. This directional dependence results in the determination of $d_\perp$, the adsorbate-substrate layer separation distance. In common cases, knowledge of this distance also fixes the chemisorption position.

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Spin Polarization of Liquid ^{3}He by Rapid Melting of Polarized Solid

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In liquid ^{3}He in a Pomeranchuk cell, spin polarizations of 5–20% have been obtained. The method involved production of polarized solid by Pomeranchuk cooling in magnetic fields from 0.03 to 3 T, followed by rapid decompression to a pressure between 2.9 and 0.2 MPa. Relaxation times in the liquid range from 1 to 5 min, increasing with decreasing pressure and with increasing field.

At low temperatures, the paramagnetic susceptibility of liquid ^{3}He tends towards a constant value because of Fermi statistics. Interactions in the liquid cause the experimentally observed limiting susceptibility[1] to be substantially higher than for an ideal gas of fermions, the enhancement factor being as high as 24 at pressures near solidification. These interactions are not yet understood. In spite of the susceptibility enhancement, spin polarization in the liquid remains small under conditions of thermal equilibrium. A field of 2.3 T is just sufficient to produce 1% polarization at the lowest temperatures and near the solidification pressure. Studies of nuclear orientation in liquid ^{3}He offer very interesting prospects, however. Among the effects of a high spin polarization predicted in recent papers by Castaing and Nozières,[2] and by Lhuillier and Laloë,[3] is a reduction of the melting pressure at low temperatures, leading eventually to a complete disappearance of the melting curve minimum near full polarization. Castaing and Nozières note that the reduction in melting pressure might tell whether the liquid owes its enhanced susceptibility to the proximity of a ferromagnetic instability. In that case the melting pressure should be suppressed below the vapor pressure, causing one or two triple points to appear in the phase diagram. The reduced melting pressure would allow studies of solid ^{3}He at lower pressures than ever before, thus increasing chances for observing the vacancy solid phase, envisaged by Andreev and Lifshitz.[4]

As a first experimental step into this field of research we have followed the suggestion of Castaing and Nozières to produce polarized liquid by melting of solid ^{3}He that has been previously polarized in a magnetic field applied at low temperature. Although the relaxation time in the polarized liquid was estimated to be some minutes, it was not clear from the outset, that polarization would survive during the time interval of melting where additional relaxation processes may be effective.

Our ^{3}He sample (^{4}He content less than 1000 ppm) was contained in the cylindrical plastic Pomeranchuk cell shown in Fig. 1. Construction details of this type of cell have been given previously.[5] The sample volume is approximately 0.15 cm^3. The cell was mounted inside the mix-

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ing chamber of a dilution refrigerator. Via a sintered powder silver heat exchanger the sample could be precooled to 15–20 mK in magnetic fields up to 2.6 T applied along the symmetry axis of the cell. For NMR detection, the cell was equipped with two saddle coils, one with two windings for high frequencies, the other with eighty windings for frequencies around 1 MHz.

Figure 2 shows a recording of the NMR line peaks during one of our compressions and decompressions. The filling capillary to the sample chamber was blocked with solid by a pressure of 3.4 MPa from the outside. The ^{3}He volume was decreased by increasing ^{4}He pressure on the outside of the flexible wall. During the compression shown, ~ 35% of the sample was solidified at temperatures between 38 and 2 mK. At the point D, compression was stopped, the sensitivity of the pressure gauge reduced, and the ^{3}He pressure on the fill line was lowered from the outside, rather slowly, to the pressure P_m corresponding to the minimum in the melting curve. Less than a second after passage of P_m, the capacitance pressure gauge at the "far" end of the cell registered an abrupt change in pressure. Within the next few seconds the ^{3}He pressure was adjusted to the value where we wanted to study the relaxation. As seen in the recording, the average polarization of ^{3}He spins in the cell is roughly conserved during the time taken for melting, after which it relaxes to the small value characteristic of the normal Fermi liquid. Relaxation appeared roughly exponential in all decompressions studied.

The most accurate relaxation times measured at various fields and pressures are shown in Fig. 3. They are of the same order of magnitude as observed in liquid ^{3}He at usual polarizations.[6] The polarization just after the decompression may be estimated by comparison with the signal from the liquid in equilibrium at temperatures below 100 mK. The background signal from ^{3}He in the surrounding mixing chamber was determined by varying the ^{3}He pressure in the cell at constant volume and using the susceptibilities in Ref. 1. The result is that we have obtained polarizations between 5 and 20% in various decompressions.

The temperature after a decompression and its change during spin relaxation could not be meas-

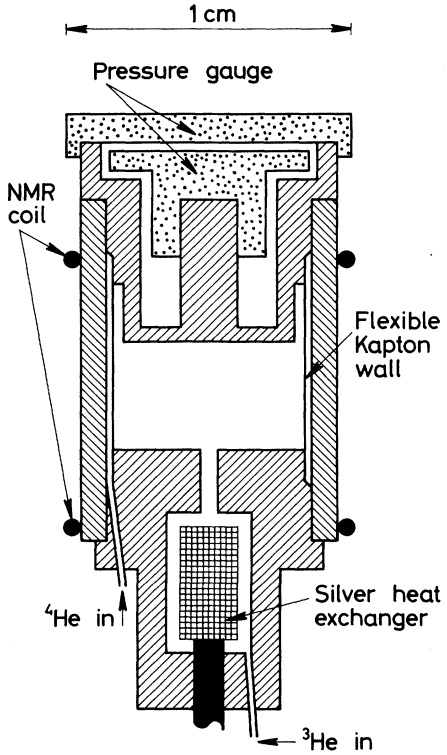

FIG. 1. Pressure cell for NMR detection during compressional cooling of ^{3}He.

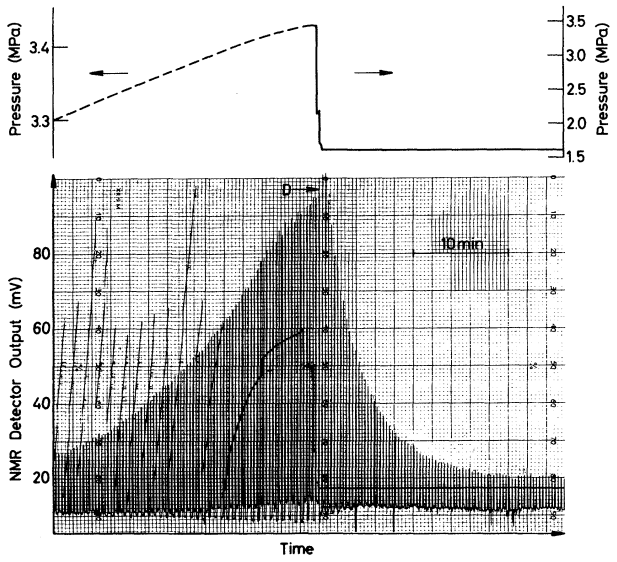

FIG. 2. NMR absorption and pressure recorded during a compression of ^{3}He followed by a decompression. On the left, magnetization increases due to solidification at decreasing temperatures. Decompression to 1.6 MPa, at D, is followed by relaxation of spin polarization in the liquid (f = 86.7 MHz, field sweep 0.5 mT, rf amplitude 3 nT). For clarity, pressure has been replotted in the upper part, as derived from the recording. Note the expanded pressure scale used before D.

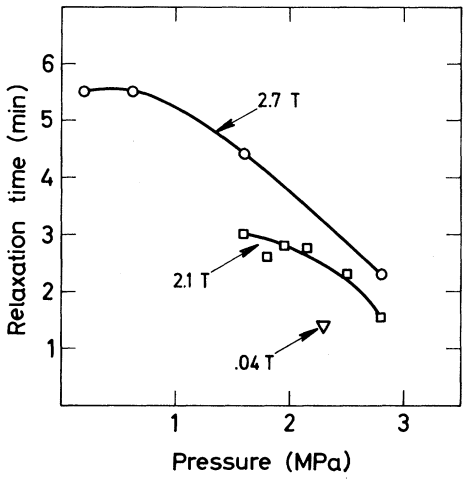

FIG. 3. Relaxation time of polarized liquid ^{3}He vs the final pressure in decompressions like Fig. 2. The applied magnetic fields are indicated.

ured in the present setup, which used only the melting pressure for thermometry.[7]

There are three questions that we want to discuss more closely below, following the sequence of events in Fig. 2.

(1) How large a polarization can be produced before the decompression? Ideally, isentropic solidification of liquid ^{3}He in a high magnetic field is a powerful method for the production of polarized solid ^{3}He. For free spins, 78% polarization corresponds to an entropy of $0.5R \ln 2$, i.e., the entropy of liquid ^{3}He around 100 mK. The applied magnetic field would determine the final temperature, not the final polarization. This polarization "efficiency" was not reached in the present work, nor in the work of Johnson *et al.*[8] Heat leaks or irreversible heat production might be causes of this limitation. Relaxation phenomena and formation of an ordered phase,[9] however, have to be considered also as possible explanations. Experimental studies of this question are in progress.

(2) How much of the polarization is lost during decompression? In the experiment recorded in Fig. 2, the resonance peak increased at the decompression. This behavior was not typical and may be due to a change in line shape. In some runs we recorded the NMR lines more precisely and found that the solid signal usually contained several smaller or larger peaks besides each other, whereas the liquid signal was more smooth. Most often, the loss in signal appeared to be in the range 10–30%. Remembering that the cell loses a significant fraction of its contents during decompression (10% to 29 bars, 23% to 2 bars) we conclude that relaxation during decompression will not be a critical limitation on the process. In a trial, when decompression was done by releasing ^{4}He pressure, we have also been able to preserve 80% of the initial polarization.

(3) Is the sample really liquid after the decompression? At the polarizations obtained, the reduction of the melting pressure predicted is of the order of 0.1 MPa, at the lowest temperatures. Therefore, it is not expected to observe solid at the pressures below P_m covered in this work. On the other hand, observation of a solid phase at pressures below the equilibrium melting curve would be of crucial importance. During our experiments we have seen indications of liquid only.

First of all, the ^{3}He fill line, originally blocked with solid, opens up in less than a second over a length of 50 cm between the point where the temperature is 330 mK and the Pomeranchuk cell (it is not just a block slippage, because the pressure gauge responds reversibly to small external pressure changes). So, a melting front propagates fast enough to melt the solid in the sample chamber in a fraction of a second. Clearly, this argument does not rule out occurrence of pieces of solid in the sample chamber, but in that case one would have to assume an inhibition of melting connected with the magnetic field or the polarization, e.g., the phenomenon of "melting triggered by spin relaxation" discussed in Ref. 2. Since the behavior in low fields (0.04 T) is similar, this possibility seems unlikely. Furthermore, if the observed relaxation were indeed associated with a slow melting of some "underpressurized" solid, then the relaxation rate should be faster with increasing underpressurization. Figure 3 shows the opposite trend, and, in general, we have not observed any discontinuity in the relaxation behavior as a function of pressure or polarization.

In conclusion, we have demonstrated the feasibility of the proposal of Castaings and Nozières[2] for nuclear orientation of liquid ^{3}He by a thermodynamical method. Relaxation times are consistent with their estimates but the polarizations expected in an ideal Pomeranchuk solidification have not been obtained. Detection of possible changes in the (nonequilibrium) phase diagram requires further work.

In parallel with our work, but using a different approach, Schumacher *et al.*[10] have performed similar studies. Their data seem consistent with

our observations.

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Equivalence of the Critical Behavior of the Quantum and Classical Heisenberg Models

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We extend Dyson's work on the mapping of the spin-S Heisenberg model onto an interacting Bose field. The operator correspondences between the two theories are established. We show that the infrared Feynman rules, which contain the critical behavior, are independent of S. Also, we explicitly check, at one-loop order, that the infrared rules generate a renormalizable quantum field theory near $d=2$ with the classical value for T_c and the exponents.

It is a well-known conjecture, in the theory of critical phenomena, that the spin-S Heisenberg model falls into the same universality class as the classical three-component model. The conjecture arose out of numerical high-temperature series work[1] in three dimensions. Here, I provide some direct analytical support within the context of the $d-2$ expansion.

In 1956, Dyson[2] demonstrated how to map the quantum model onto an interacting Bose system. I extend this work with a modern emphasis on the infrared Feynman rules. I have the following new results. By adding local sources, I connect Bose and spin operators. Then I show that the finite-S, infrared diagram rules are identical to the $S\to\infty$, infrared rules. This establishes that the parameter S is technically irrelevant. Also, these particular $S\to\infty$ rules are not manifestly the same as the rules of the nonlinear σ model.[3] They are much simpler, even though they generate the same diagrammatic expressions. I will elaborate on these below and also discuss the one-loop renormalization of this theory near $d=2$; I verify that, as expected, T_c and the exponents have the correct values.

First, I summarize some of Dyson's results; detailed arguments may be found in Ref. 2. The partition function of the isotropic, spin-S Heisenberg model is given by $Z=\mathrm{Tr}_S[\exp(-\beta H)]$, where

$$H=-S^{-2}\sum_{i,j}J(i-j)\vec{S}(i)\cdot\vec{S}(j). \tag{1}$$

The indices i, j range over the N sites of a d-dimensional space lattice. $J(i)$ is short range. The trace extends over $(2S+1)^N$ states. Also, $\vec{S}^2=S(S+1)$, and $[S^x(i), S^y(j)]=iS^z(i)\delta_{i,j}$, plus cyclic