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Résumé.- Comme avenir de la recherche sur les très basses températures, on peut prévoir par exemple, la découverte de nouvelles phases exotiques, l'observation éventuelle du "percement macroscopique quantique" dans le vide, et l'amplification des interactions très faibles de la physique des hautes énergies.

Abstract.- Why the continuing search for ultralow temperatures ? Possible motives include the prospect of exotic new phases, of observing macroscopic vacuum quantum tunnelling and of amplifying the ultra-weak interactions postulated in particle physics.

As its title implies, this talk is much more speculative than most "reviews". I'll attempt a partial answer to the question : Why do we believe the quest for ultralow temperatures is worthwhile ? What fundamentally new physics is peculiar to this region? I'll deliberately say little about areas covered in other theoretical review talks , but even so the selection of topics is highly personal; almost all of them are associated in some way with the phenomenon of macroscopic quantum coherence, usually of the superfluid type. They range from questions just becoming experimentally accessible to some which may, at best, be a decade or two away or, at worst, be a mere theorist's playground.

1. NEW PHASES.- A general feeling which probably motivates most low-temperature physicists is that by going to lower and lower temperatures we are likely to see more and more subtle types of ordering. One obvious reason is that the energies associated with such ordering are often very small, corresponding to temperatures in the mK region or below (exchange energy in solid ^{3}He, nuclear dipole energy in other solids, etc.). Rather less obviously, if the ordering is very delicate, involving for instance complicated angular correlations, it will be destroyed very easily by any kind of incoherent scattering and so will not occur until temperatures so low that the scattering is much reduced (or the energy advantage from the ordering is much increased). As an example, the very "delicate" B-phase of superfluid ^{3}He, involving three types of Cooper pairs with subtle spin and angular correlations, is suppressed by boundary or other scattering in favour of the cruder and more robust A phase. Existing highly ordered bulk low-temperature phases include of course superconductivity, superfluid ^{4}He, ^{3}He-A and B, magnetically ordered solid ^{3}He, nuclear dipole ordering in solids.. Here I'll discuss two plausible candidates for addition to the list in the next few years.

First, there is p-wave superconductivity in metals. Possibly, in some metals the ordinary phonon-exchange interaction favours p-wave superconductivity /1/, but the most promising candidates seem to be metals which are so strongly paramagnetic as to be almost unstable against ferromagnetism, so that the Stoner parameter $\bar{I}$ is only just less than 1. In that case theory predicts /2/ that the exchange of virtual paramagnons (long-lived spin fluctuations) should suppress s-wave pairing and favour p-waves; however, rather surprisingly at first sight, the transition temperature T_c does not continue to increase as $\bar{I} \to 1$ (i.e. as the ferromagnetic instability is approached) but rather goes through a maximum /3,4/, of the order of 10^{-2} - 10^{-3} times the Fermi temperature, when $\bar{I}$ is close to 1 and then drops to zero as the instability is approached. The pure metal which is nearest to ferromagnetism is Pd, but calculations for this system /3/ predict a T_c of the order of only 10^{-5} K, which is presumably not attainable in the near future. Ideally, one would like to take an alloy system such as Ni-Rh, where by varying the composition we can vary $\bar{I}$ smoothly through 1, thereby inevitably crossing the point where T_c is a maximum. Unfortunately, p-wave superconductivity is a "delicate" phase, and unlike the usual s-wave type is very easily destroyed by the scattering which inevitably occurs in alloys /1/. The best hope would seem to be if we could find a system where the ferromagnetic transition could be induced by varying some parameter other than composition; one possible candidate /5/ might be the weak itinerant-electron ferromagnet /6/ $Zr\ Zn_2$, where the ferromagnetism is suppressed by a pressure of about 8 kbar.

What would be specially interesting about a p-wave superconductor ? For a start, if the attraction binding the Cooper pairs is indeed largely due to paramagnon exchange, then it is very probable we would get an anisotropic p-wave phase like superfluid ^{3}He-A, with all the associated unusual topological properties /7/. However, we would now have the bonus that the currents couple directly to the electromagnetic field, so it should be possible to display these topological properties quite directly and spectacularly; for instance, the behaviour in a magnetic field is likely to be quite different from that of ordinary s-wave superconductors of either type. (The situation may be further complicated by the fact that lattice anisotropy, or defects, may tend to pin down the orientation of the Cooper pairs /8/).

A perhaps more promising candidate for our next new low-temperature phase is the predicted BCS-paired phase of dilute solutions of ^{3}He in liquid ^{4}He. At the moment, the upper limit on the transition temperature is 1.5 mK (at 21 bar)/9/. At first sight one might expect the transition to lie in the microdegree range, for the following reason : Consider the standard weak-coupling BCS expression for the transition temperature

$$T_c = \text{const.}\ \omega_c \exp - 1/N(0)\ V_{eff} \qquad (1)$$

where ω_c is a cutoff energy for the pairing interaction V_{eff} between quasi-particles near the Fermi surface and N(0) is the density of states there, and compare dilute solutions of ^{3}He in ^{4}He with pure ^{3}He, for which T_c is a few mK. V_{eff} is expected to be of the same order of magnitude in the two systems, while N(0) is much smaller for solutions; hence, at first sight, T_c should be depressed by an exponentially large factor. However, by the same argument one would expect T_c in pure ^{3}He to be exponentially sensitive to N(0), whereas the experimental dependence is much weaker. Indeed, if we were to extrapolate this dependence to the value of N(0) occurring in the most concentrated dilute solutions, we should find a T_c of the order of 10^{-4} K. Clearly this procedure is much too naive, but several recent calculations have indeed come up with a figure of this order or even somewhat larger /10/.

A BCS phase of dilute ^{3}He-^{4}He solutions would be of extreme interest for the general theory of Cooper pairing. Three variables - ^{3}He concentration, pressure and magnetic field - can be varied over substantial intervals. Present theory predicts that at low concentration the pairing will be in a $^1S_0$ state as in superconductors, while at higher concentrations a ^3P state like that found in pure ^{3}He will become stable. Now, the existence of the A phase in pure ^{3}He is generally believed to depend crucially on the phenomenon of spin fluctuation feed-back /11/ (the spin polarizability of the medium, which provides the mechanism of attraction forming Cooper pairs, is itself strongly modified by the onset of pairing). In mixtures this effect should be nonexistent or at least very much reduced, (since the attraction is largely due now to (density) polarization of the inert ^{4}He background) and we would therefore expect only a B-type phase to occur; this would constitute a crucial test of the spin fluctuation hypothesis. The low-concentration $^1S_0$ phase would be even more interesting, since it would be our first (laboratory) example of a neutral and impurity-free s-wave Fermi superfluid. One point of particular interest is that a magnetic field of a few hundred gauss should probably stabilize the so far hypothetical Fulde-Ferrell phase /12/, in which the order parameter undergoes a complicated spatial variation; in superconductors this ultra-"delicate" phase is thought to be inevitably suppressed by a combination of the Meissner effect and impurity scattering. Finally, there is the intriguing possibility /13/ that the ^{4}He-mediated interaction between ^{3}He impurities is strong enough that even two isolated ^{3}He atoms form a weakly-bound molecular state. If so, then by varying the concentration we may be able to study experimentally the transition between the "Cooper-pair" limit, where the formation of pairs and their Bose condensation are one and the same process, to the "diatomic-molecule" limit, where they are quite different.

2. QUANTUM PURITY : TRUE AND FALSE VACUA.-

Let's now turn from the subject of possible new phases to the question of what fundamentally new physics we can do with the ones we have already. As we decrease the temperature, at least two important things happen : the number of thermal excitations decreases rapidly, and ultra-weak interactions may become important. The effects of these are discussed in this and the next section respectively.

Consider first the case where all elementary excitations of the system are bosons (e.g. phonons) and let the thermal reduced de Broglie wavelength at temperature T be λ_T. Then, crudely speaking, any subsystem of volume much less than λ_T^3 will contain no excitations, i.e. it will be in its quantum-mechanical groundstate. For orientation, λ_T for liquid or solid helium at 1 mK is of order 1 micron. Fermion excitations in a normal system are more difficult to remove, but in a superconductor or isotropic Fermi superfluid they vanish dramatically as the temperature is reduced; for $T \lesssim 0.03\ T_c$ there is less than one fermion quasiparticle per cubic centimetre ! Moreover, those few excitations which do still exist have very long mean free paths - limited, at temperatures of this order, by the dimensions of the sample.

Thus, in some many-body systems at low temperatures we have precisely the vacuum which particle theorists dream about; moreover, in many cases this vacuum has a nontrivial structure and even one which we can control experimentally and cause to vary in space. Some aspects of this situation are explored in the talk by Maki /14/; however, there are many others which are connected specifically with the "quantum purity" of the vacuum. As a first illustration, consider a sample of superfluid ^{3}He-A in which, by imposing suitable geometric constraints and magnetic fields, we have caused the orientation of the anisotropic Cooper-pair wave function (the so-called $\underset{\sim}{\ell}$-vector) to vary in space. Then consider the ballistic motion of a quasiparticle against this background If it has wave vector $\underset{\sim}{k}$, its energy is proportional to $E_k \equiv (\varepsilon_k^2 + |\Delta_k|^2)^{\frac{1}{2}}$, where $\Delta_k \equiv \Delta_o\, \underset{\sim}{k} \times \underset{\sim}{\ell}$ is a function of the direction of $\underset{\sim}{\ell}$; thus, E_k is varying in space and the ballistics is nontrivial. It turns out /15/ that if the quasiparticle is fired off in a given direction, it executes a sort of boomerang motion and returns, nearly, to its starting point (a complicated kind of Andreev reflection). To see this kind of effect (in practice, probably through measurements of viscosity or thermal conductivity) we require only temperatures low enough that the quasiparticle mean free path is comparable to the sample dimensions; for ^{3}He-A this is by no means an exorbitant demand.

Much more intriguing, however, are the prospects opened up by the existence of <u>different</u> vacua of the same physical system. In particle physics the problem of vacuum instability, along with the closely related question of "instantons", has received a great deal of attention in the last two or three years /16,17/. Suppose for instance we have a nonlinear field theory involving a real scalar field ϕ with a potential $V(\phi)$ which has both an absolute minimum and one or more metastable local minima. It is conceivable that the Universe, during its first few (rapidly cooling) minutes of existence, settled as it were by mistake into a metastable local minimum (in the language of metallurgy, it was "quenched"). Since on the scale of particle physics the temperature is (now) essentially zero, this metastable state is stable against thermodynamic fluctuations. However it could in principle make the transition by means of (macroscopic) quantum tunnelling. There are by now a number of calculations of the transition probability /16,17/; all of them proceed by assuming that, just as in the standard thermodynamic nucleation theory, a "bubble" of the stable phase forms and must then expand against the interphase surface tension to a critical size, after which it can expand freely and fill the Universe. All calculations indicate that the transition probability is proportional to $\exp(-A_c/\hbar)$, where the "critical action" A_c is, apart from a numerical constant, the energy of the (three-dimensional) critical bubble times the time for a light wave to cross it. Such calculations are of course impossible to compare with experiment, if only because once this "little bang" has taken place we shall presumably be in no state to record the fact !

However, there are several situations in low-temperature physics which are almost exactly analogous (and are fraught with less danger to the experimenter). One case which has been considered in detail in the literature /18,19/ is a solid which has been supercooled in a metastable crystallographic phase; however, this may be rather difficult to explore experimentally owing to the presence of dislocations, etc... Possibly more promising might be a superconducting loop containing a weak link (of the type used in SQUIDS) through which a variable external magnetic flux Φ_x is applied. In the simplest model /20/ the potential energy of the system is

$$U(\Phi) = \frac{1}{2}\ \frac{(\Phi - \Phi_x)^2}{L} - i_c\ \frac{\Phi_o}{2\pi} \cos \frac{2\pi\Phi}{\Phi_o} \tag{2}$$

where Φ, here regarded as a dynamical variable, is the total flux through the loop, L its self-inductance, i_c the critical current of the weak link and $\Phi_o \equiv h/2e$ the flux quantum. For $Li_c > \Phi_o$ and suitable values of Φ_x the function $U(\Phi)$ has one or more metastable local minima; moreover, the height of the barriers separating them from the true minimum can be adjusted by varying Φ_x. If this barrier height is not too large compared to the thermal energy k_BT, the system can jump from the metastable to the true minimum by classical thermodynamic fluctuations; the theory of this has been worked out /20/ and is in good agreement with the experiments /21/.

However, one can also consider the possibility that the system tunnels quantum mechanically through the potential barrier. This arises because in addition to the "potential energy" $U(\Phi)$ the circuit also possesses a "kinetic energy" $\frac{1}{2} C \dot{\Phi}^2$, where C is the capacitance of the junction /20/ (we neglect resistance for the moment). If we assume that we can apply the standard canonical quantization procedure to the macroscopic dynamical variables Φ and $\dot{\Phi}$, then it is straightforward to estimate the quantum tunnelling probability and show that it is dominant when

$$k_BT << \hbar \omega_o, \ \omega_o \ \equiv (1/LC)^{\frac{1}{2}} \ (\Delta\Phi_x / \Phi_o)^{\frac{1}{4}} \qquad (3)$$

where $\Delta\Phi_x$ is the difference of the external flux Φ_x from the value at which the metastable minimum becomes unstable. For realistic point-contact weak links this requires only moderately low temperatures ($\lesssim$ 0.1 K). However, the above estimate applies only to circuits where normal resistance can be neglected; to take this into account in the quantum tunnelling calculation appears a non-trivial problem. If it is indeed possible to display macroscopic quantum tunnelling in this system, it should provide some amusing sidelights on the quantum theory of measurement!

The above example is what field theorists would call a "zero-dimensional" case : only one pair of dynamical variables (Φ and its conjugate momentum) are involved. An example possibly closer to the vacuum tunnelling of particle physics is the $A \rightleftarrows B$ transition in superfluid ^{3}He. If this transition nucleates in bulk liquid at all, whether thermodynamically or quantum-mechanically, it should do so by the usual bubble-formation mechanism, with a "critical bubble" radius R_c which in general should be a few times the coherence length ξ_o. If we now simply take over the particle-physics result for the quantum tunnelling probability by replacing the speed of light by some effective velocity c_s associated with the oscillations which if sufficiently amplified lead to the transition, then the ratio of the (negative) exponents for quantum tunnelling and classical nucleation is about $4R_c/\lambda_T$, where λ_T is the reduced thermal de Broglie wavelength of the oscillation in question. Any reasonable estimate of c_s then leads to the result that quantum nucleation certainly dominates for $T \lesssim 0.05\ T_c$, and possibly even for $T \sim T_c$. In view of our present utter lack of understanding of the nucleation mechanism in superfluid ^{3}He, I believe a proper calculation, with due attention to the effects of dissipation in the normal component, is highly desirable. At any rate there seems a real possibility that ultra-low-temperature physics can eventually serve as a "laboratory of instantons" just as it is already /14/ a "laboratory of solitons" !

3. AMPLIFICATION OF ULTRA-WEAK EFFECTS.- Finally, bringing our feet perhaps slightly closer to the ground, let us briefly review some of the ways in which the characteristic coherence of low-temperature condensed phases, particularly superfluid ones, can amplify effects much too small to be seen at the level of individual atoms or molecules. Perhaps the simplest illustration /22/ is the very small orbital magnetic moment μ_{orb} associated with the rotation of a homonuclear diatomic molecule, as a result of the fact that the electron cloud of each atom is slightly distorted by its neighbour (an intrinsically "chemical" effect which vanishes in the limit of zero overlap of the clouds). Any such magnetic moment is obviously directed along the orbital angular momentum vector or axis of rotation, of the molecule. Now in an ordinary gas of diatomic molecules, in the absence of a magnetic field, the orientation of this axis is completely random, so the net magnetic moment averages to zero; and though an external field H should in principle have an orienting effect, the ratio $\mu_{orb}H/k_BT$ is so tiny that the effect is usually not directly detectable. Suppose however we consider the anisotropic superfluid phase ^{3}He-A. Here we have Cooper pairs, which for present purposes are just giant diatomic molecules, and we expect a very weak orbital magnetic moment directed along the axis of rotation of each pair. But now, in contrast to the gas of diatomic molecules, the pairs are automatically Bose-condensed, which means the axis of rotation is the same for all pairs. Thus, the magnetic moments add up coherently and the system behaves as a (very weak) liquid ferromagnet. This effect has recently been detected /23/; notice that it is probably the first observation of a (static) genuinely chemical effect in pure helium of either species ! One of the more exciting possible applications of the general principle involved here is to look for possible macroscopic consequences of the weak interaction. According to most models currently favoured

by particle theorists, there should exist apart from the so-called "charges-current" processes responsible for events such as nuclear beta-decay, "neutral-current" effects which inter alia produce an additional interaction, over and above the usual electromagnetic one, between electrons and nucleons /24/. This interaction is fantastically weak compared to electromagnetism, but it has the unique property of violating parity conservation (P) (and possibly, to a very small degree, also time-reversal invariance (T)). Intensive searches for the effects of such an interaction have been carried out in the last two or three years by spectroscopic and scattering experiments on atoms, and a few weeks before this Conference the first positive results were announced /25/. To get an idea of the difficulty of these experiments, we note that the strength of the interaction in hydrogen is only about 10^{-15} eV, i.e. about 10^{-16} of the Coulomb interaction, and even in heavy atoms it is still only about 10^{-8} eV at most. For this reason it would almost certainly be quite hopeless to look for equilibrium effects on the atomic scale.

The question now arises : Is it possible to use the coherence properties of ultra-low-temperature systems to amplify this ultra-weak interaction so that it can produce a macroscopic effect ? Several experiments along these lines have been proposed, although whether they can be made competitive with the established atomic techniques as a promary source of information about the weak interaction - indeed whether they are currently feasible at all - depends on a complicated combination of technical factors in each case. I'll briefly describe two proposals, both of which are designed to look for the P-violating but T-conserving component of the neutral-current electron-nucleon interaction, and which illustrate different aspects of superfluid coherence. The interaction in question contains, among other things, a term of the form $\zeta\underset{\sim}{\sigma}_n\cdot\underset{\sim}{p}\ \delta(\underset{\sim}{r})$, where $\underset{\sim}{\sigma}_n$ is the nuclear spin, $\underset{\sim}{p}$ the electron momentum and ζ a constant : the $\delta(r)$ indicates that the interaction is a "contact" one, i.e. there must be a finite probability of finding the electron at the nucleus. For electrons in a typical heavy atom or solid the strength of this interaction is of order 10^{-10} eV or less, that is, very much less than the thermal energy k_BT. The first proposal /26/ to amplify the effect presupposes the production and maintenance of a high degree of nuclear spin polarization in a superconducting metal. Then the quantity $\zeta\underset{\sim}{\sigma}_n$ is coherent over the sample and plays the same role as a magnetic vector potential $\underset{\sim}{A}$; and in a superconductor, because of the macroscopic coherence of the Cooper pair wave function, this leads to the well-known phenomenon of flux quantization with a ζ-dependent modification which is in principle detectable. Notice that it is the coherence of the centre-of-mass motion of the Cooper pairs which is important here.

The second proposal /27/ relies by contrast on the coherence of the relative motion of the Cooper pairs in ^{3}He-B. It is well known that a particle, atom or molecule can normally possess an electric dipole moment $\underset{\sim}{d}$ only if both P and T are violated. For since the only characteristic vector describing a stationary state is $\underset{\sim}{J}$, we should have to have $\underset{\sim}{d} = c\underset{\sim}{J}$, which obviously violates both P and T. On the other hand, imagine for the moment that our system possessed two conserved angular momentum vectors, say an orbital angular momentum $\underset{\sim}{L}$ and a spin $\underset{\sim}{S}$. Then we can write $\underset{\sim}{d} = c\ \underset{\sim}{L} \times \underset{\sim}{S}$, which violates P but not T, as required for present purposes. Now in an ordinary atom or molecule, $\underset{\sim}{L}$ and $\underset{\sim}{S}$ are not separately conserved but precess around their resultant $\underset{\sim}{J}$, so that $\langle\underset{\sim}{L} \times \underset{\sim}{S}\rangle$ is zero in a stationary state. More significantly, even if for a given atom it were nonzero, in an ordinary gas the atomic orientations would be completely random so that $\langle\underset{\sim}{L} \times \underset{\sim}{S}\rangle$, and hence the electric dipole moment, would average to zero. So even if the P-violating dipole moment exists, it seems impossible to see it in any ordinary system.

But now consider superfluid ^{3}He-B. The Cooper pair wave function for this phase is obtained by starting with what for a diatomic molecule would be just a ^3P_o state ($\langle\underset{\sim}{L}\rangle = \langle\underset{\sim}{S}\rangle = \langle\underset{\sim}{L} \times \underset{\sim}{S}\rangle = 0$) and then rotating the spin coordinates relative to the orbital ones around some axis $\underset{\sim}{\hat{\omega}}$ through an angle θ. The new state has $\langle\underset{\sim}{L}\rangle = \langle\underset{\sim}{S}\rangle = 0$, but $\langle\underset{\sim}{L} \times \underset{\sim}{S}\rangle = -\frac{4}{3}\sin\theta.\underset{\sim}{\hat{\omega}} \neq 0$. Now, what is crucial is that from the very nature of the superfluid state the Cooper pairs must be Bose-condensed, that is they must all have identical relative as well as centre-of-mass wave functions; thus, $\hat{\omega}$ and θ are the same for all pairs and any electric dipole moment along $\underset{\sim}{L} \times \underset{\sim}{S}$ adds up coherently over the whole liquid to produce a macroscopic effect. To be sure, the fact that it is macroscopic in the technical sense (i.e. proportional to the total volume of liquid) by no means implies that it is large, and it is even a question whether it is measurable with existing techniques. Nevertheless, the mere existence of this and other macroscopic effects of the weak interaction is itself a dramatic illustration of the unique nature of the phenomena to be found at ultra-low temperatures.

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