

NEUTRINO AND DARK-MATTER DETECTION AT LOW TEMPERATURE

The use of low-temperature techniques to see tiny energies in massive detectors may be opening a 'low energy' frontier of particle physics.

Leo Stodolsky

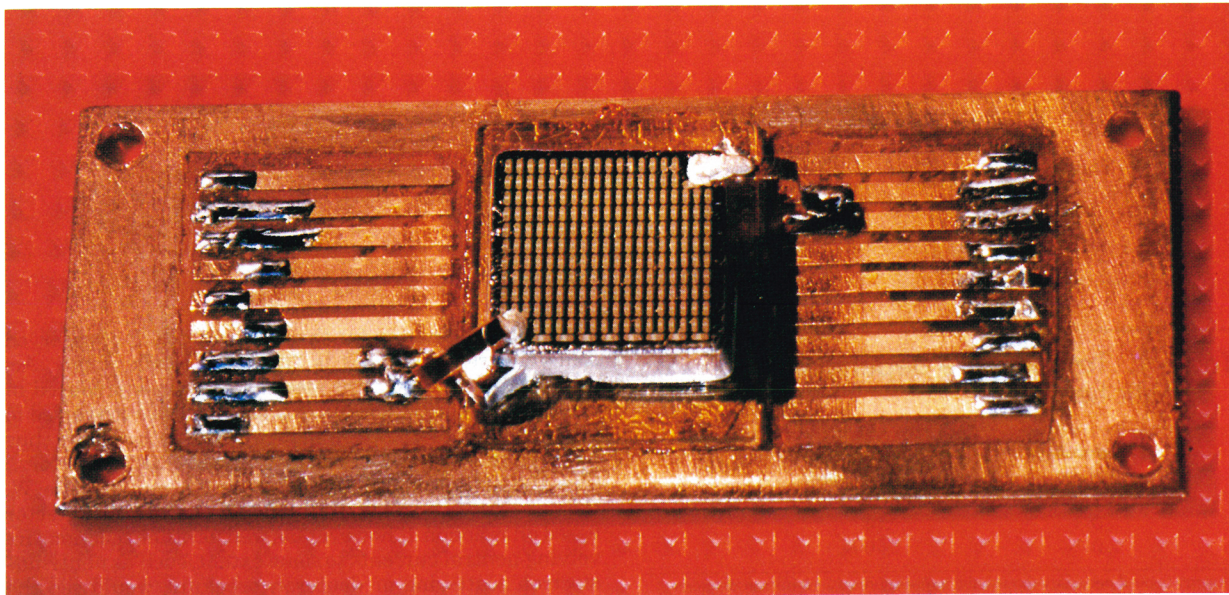
It is with shock, and with new respect for the subtleties of condensed matter physics, that the noninitiate (such as I was) first realizes that at low temperatures a microscopic energy—like that associated with a single atom—can be enough to seriously affect the state of a macroscopic body.

Table 1 shows the energy necessary to raise the temperature of a small sphere of tin by 10 millikelvin at various low temperatures. At 300 mK, for example, 14 eV can produce this temperature jump in a 10-micron sphere. The tin is in the superconducting state, so if the little grain is held 10 mK below the superconducting-normal phase boundary by a magnetic field, the 14 eV can flip it to the normal state. In other words, with 14 eV—the binding energy of the hydrogen atom—we can dramatically change the state of 10^{13} atoms. Furthermore, the collapse of the magnetic field around the grain delivers an observable signal that we can use to read out the process.

The realization that great energy sensitivity is possible at low temperatures has led in recent years to a burst of research activity and a series of developments in cryogenic particle detectors¹ (see figure 1 for an example). The prospect of intriguing applications to fundamental problems in cosmology, neutrino physics and weak interactions has produced many ingenious if not sometimes wild ideas, a number of which are actually under development.

The idea of using low-temperature methods to detect radiation is of course nothing new, and without making any particular effort at a systematic historical survey, I have run across references to the subject as far back as the 1930s and 1940s.² The current wave of interest may be traced to the possibility of meeting two almost mutually exclusive demands: the need to use massive amounts of detecting material on the one hand, and the need for very high energy sensitivity or resolution on the other. Furthermore, we wish to detect the radiation on an event-by-event basis, as in an ordinary particle detector, and not, say, through the steady warming of a cold sample, as in radiometry. If the detector is relatively massive we can search for rare processes involving the usual weak

Leo Stodolsky is a director of the Max Planck Institute for Physics, in Munich, Germany.



Superconducting detector. This array of 432 series-connected superconducting tunnel junctions was fabricated on the surface of a 2.2-gram single crystal of indium, which acts as a particle absorber. (Courtesy of Norman Booth, University of Oxford, UK.) **Figure 1**

interaction or even weaker interactions. If it has great energy sensitivity or resolution, new observations become possible, of a kind previously not attempted in particle or nuclear physics. Also, we can substantially improve some existing techniques. The possibility of greatly improved methods for detecting medium- and low-energy neutrinos using low-temperature methods and the further possibility of directly detecting the dark matter of the universe have drawn particular attention.

Coherent neutrino scattering

Coherent nuclear scattering in the electroweak standard model was first calculated by Daniel Z. Freedman in 1974. The proposal to use the process for neutrino detection came a decade later.^{3,4} This process (on a nucleus A) can be represented as



This has the largest known cross section of any low-energy neutrino reaction, but the only thing to look at in the final state is the recoil of A , and because this recoil is very small, detection is not possible by conventional methods. The process goes via the so-called neutral-current mechanism of the electroweak interaction. The existence of this kind of weak interaction, where, in contrast to the old "charged current" or inverse beta mechanism $\nu_e A_Z \rightarrow e A_{Z+1}$, the lepton need not change its charge, was suspected for many years and was first definitively established in the early 1970s in high-energy neutrino experiments. It has since become a cornerstone of the electroweak standard model. Because in reaction 1 the struck nucleus need not change its internal state, the scattering can be coherent, and so in calculating the cross section we sum the amplitudes over the nucleons in the nucleus before squaring. The total elastic cross section then turns out to be, approximately,

$$\sigma = \frac{G^2}{4\pi} N^2 E^2 \quad (2)$$

Here N is the number of neutrons in the nucleus and E is

the neutrino energy. The process, albeit of short range, is closely analogous to Rutherford scattering, the elastic scattering induced by the ordinary Coulomb interaction. The charge-squared factor Q^2 of Rutherford scattering becomes a "weak charge"-squared factor here. Both the neutrino and the nucleons possess "weak charges." For nucleons, according to the algebra of the standard model, this charge is proportional to $Q = 4 \sin^2 \theta_w$. Experimentally, it is found that the weak-interaction angle factor $\sin^2 \theta_w$ is close to $1/4$. Therefore for protons the weak charge is about 0, leaving us with only the number of neutrons N in the amplitude, and thus equation 2.

The factor N^2 can be quite large, on the order of 10^4 for a heavy nucleus. This leads to cross sections for medium- and low-energy neutrinos that are unusually large relative to inverse beta decay, for which the cross section is very roughly given by leaving out the N^2 factor. The cross section of course remains quite small in any absolute sense: For a 1-MeV neutrino, the cross section of a lead nucleus is still only about 10^{-40} cm^2 .

Nevertheless, the N^2 factor endows reaction 1 with considerable attraction as a detection reaction. One can appreciate this by considering the reaction rates at a large reactor. Table 2 shows some rates for reaction 1 per kilogram of detection material to be expected near a large reactor. These figures suggest that the tons previously needed for detection of the inverse beta process could now become kilograms. Or take the detection of solar neutrinos. Current projects give detection rates of several to some hundreds of solar-neutrino units ($1 \text{ SNU} = 10^{-36}$ reactions per target atom per second). Equation 2, however, can give thousands of SNU. Even after accounting for the sacrifices necessary for practical implementation of such detection schemes, the figures remain quite interesting.

Neutral currents, solar and terrestrial

Neutral currents and the nuclear coherence factor offer a special advantage, of course, only for a certain neutrino energy range, namely, those energies where the probabili-

Table 1. Temperature dependence of specific heat*

Temperature (kelvin)	Energy (electron volts)
1.0	1000
0.3	14
0.1	0.6

*Energy deposit necessary to raise the temperature of a 10-micron-diameter sphere of tin by 10 millikelvin at various low temperatures.^{4,13}

ty that the nucleus remains in its ground state is a dominant part of the cross section. This condition obtains when the typical recoil momentum Δ experienced by the nucleus is not too large—specifically, when $R\Delta < 1$, where R is the radius of the nucleus. This in turn corresponds to an incident neutrino energy of up to some several tens of MeV. It is in just this energy range that we have the neutrinos from reactors, from the Sun, from supernovas and from the radioactivity of the Earth. This is not an accident, of course: These neutrinos are themselves nuclear in origin, and so it is not surprising that their wavelengths are of nuclear dimensions, where nuclear coherence dominates. At higher energies the coherent elastic scattering is still there, but because neutrino cross sections generally increase with energy, it is overtaken in magnitude by inelastic processes, and we come into the domain of more familiar detection techniques.

Another aspect of reaction 1 connected with its neutral-current character is that it yields the same cross section for all neutrino types: ν_e , ν_μ , ν_τ , antiparticles included. This is a consequence of the fact that in the electroweak standard model the neutral current is induced by exchange of the weak intermediate boson Z^0 , which is coupled equally to all neutrinos. This feature of reaction 1 could turn out to be particularly important in connection with the solar-neutrino problem. An often

Table 2. Interactions detected by grain flipping*

Material	Threshold energy (electron volts)	Rate 1 (per kg-day)	Rate 2 (per kg-day)
Tin	100	84	50
Lead	20	380	320
Lead	100	75	42

*Detection rates for reaction 1 by the grain flipping mechanism near a large reactor providing a flux of $10^{13}/\text{cm}^2 \text{ sec}$. The threshold energy is the energy assumed to be necessary to flip the grain. For rate 1 it is assumed that all recoils above the threshold energy lead to a flip, while for rate 2 it is assumed that 30% of the recoil energy is lost.⁴ The direct application of equation 2 with no such corrections would yield 700 per kg-day for lead.

discussed explanation for the apparent deficit of observed solar electron neutrinos is “neutrino oscillations.” According to this hypothesis electron neutrinos produced in the center of the Sun by nuclear reactions are converted to other types of neutrinos on their way to Earth and are thus not seen in the solely ν_e -sensitive inverse beta detectors.⁴ (See the article by Lincoln Wolfenstein and Eugene W. Beier in *PHYSICS TODAY*, July 1989, page 28.) A detector based on reaction 1, however (as well as other reactions involving neutral currents to some extent, such as neutrino-electron scattering or deuteron breakup), would see the neutrinos that have “disappeared” from the ν_e flux.

In addition to the interest higher-rate neutrino detection has for research in astrophysics and neutrino physics, there would be applications in other fields for a relatively small and movable neutrino detector. The capability to monitor nuclear reactors from the outside would be a valuable asset in nuclear safety work, for example.

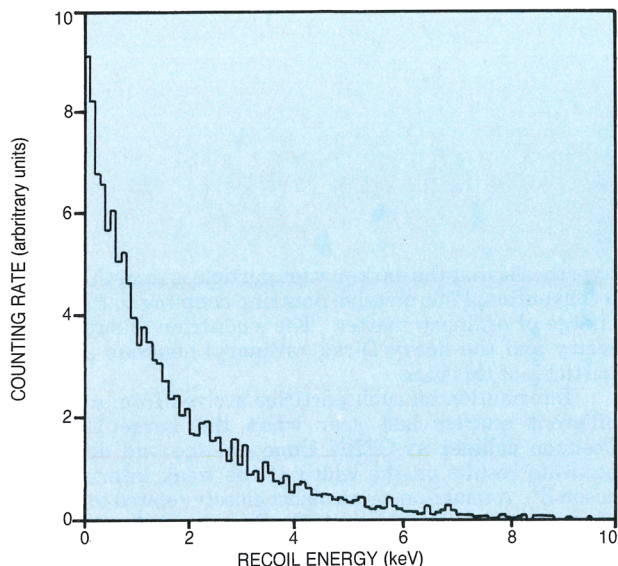
And then there is the particularly intriguing prospect of “neutrino geology.” The flux of terrestrial neutrinos is a direct reflection of the rate of radioactive decays in the Earth and so of the associated energy production, which is presumably the main source of the Earth’s heat.⁵ Thus it would clearly be of the greatest interest for our understanding of the history of the Earth and its geothermal balance to be able to measure terrestrial neutrinos, particularly with a mobile instrument. There is also the possibility of attractive applications in other geological studies and in mineralogical exploration.

The future of such terrestrial-neutrino measurement is tied up with the clarification of the solar-neutrino problem—that is, the seeming deficit of observed solar neutrinos. The Sun, through fusion, sends us neutrinos, and the Earth, through fission, antineutrinos. Because the neutral-current detector is sensitive to both, the solar neutrinos will act as background in the measurement of terrestrial neutrinos. Ideally, for neutrino geology we would like a light, high-rate detector sensitive only to antineutrinos, but there seem to be no suitable basic processes. Estimates of the terrestrial-neutrino flux⁵ suggest a possible “window” in the presumably more intense solar neutrinos in a region above 2 MeV.

Opposed to these and other attractive prospects is the formidable task of observing reaction 1, which to the high-energy or nuclear physicist looks very much like nothing in-nothing out. The magnitude of the problem is easy to see: The recoil energy of the nucleus is given by

$$E_{\text{recoil}} = \frac{\Delta^2}{2M_A} \quad (3)$$

This has its maximum for backward scattering, where the momentum transfer Δ is $2E_\nu$ (in units where $c = 1$), and has an average value of $1/3$ of the maximum. For a 1-MeV neutrino incident on aluminum, this equation yields an average recoil energy of 25 eV. The recoil energy goes quadratically with the incident energy and inversely as



the mass M_A of the nucleus. Thus at the upper end of our range, with several tens of MeV incident, the recoil energy would reach into the tens of keV; at the lower end on a heavy nucleus we have merely electron volts. These numbers are daunting to the high-energy physicist, who although by now accustomed to looking for very rare or perhaps nonexistent things, like proton decay or the top quark, at least has the right to ask for them to look rather dramatic. Here we seem to have the worst of both worlds: rare events with a very low energy.

On the other hand, the vistas unfolding seem sufficiently broad and the technological problems sufficiently interesting to tempt serious consideration of how to observe these small energies. This seems possible only by using low temperatures.

Dark matter

The idea of sensitive new detectors got considerable impetus and further motivation from the realization that if a detector for such small nuclear recoils is conceivable, then it is also conceivable that one could directly detect some of the proposed forms of "dark matter," the famous missing mass of the universe.⁶ The dark, or nonluminous, matter is without doubt one of the most fascinating puzzles of the present day. The presence of much dark matter in the universe—probably constituting a majority of the universe's mass-energy—is almost universally accepted by astronomers. It is evidenced by the constant rotation curves of spiral galaxies: The velocity of material far from the optical center of the galaxy does not decrease with distance, an apparent violation of Kepler's law unless the galaxy has an extended dark halo. It also is supported by other observations, such as the virial behavior in clusters of galaxies. And because there doesn't seem to be enough observed visible matter to close the universe in cosmology, the existence of dark matter would fit with the aesthetic desire to get to the right matter density for the simplest, spatially flat universe.

Proposals for the solution to the "dark-matter problem" range from the mundane, such as the idea that the dark matter consists of big planets or burned-out stars, to the incredible, such as changing Newton's second law. Somewhere in between, and still quite fascinating, is the possibility that the dark matter consists of some elementary-particle relic of the early instants of the Big Bang, one that is sufficiently weakly interacting that its effects at

Recoil-energy spectrum that would be induced by dark-matter particles of mass 10 GeV scattering off silicon nuclei. In this simulation the root-mean-square velocity of the particles is 300 km/sec, and there is a cutoff maximum velocity set at 600 km/sec by the escape velocity from the Galaxy. (Courtesy of Susan Cooper, Max Planck Institute, Munich.) **Figure 2**

present are purely gravitational.⁷

In one popular proposal, the relic particle, now presumably orbiting in our galaxy and forming its dark halo, is something like a heavy neutrino—a weakly interacting massive particle, or WIMP. Many theorists in particular like the idea that the WIMP would be the first manifestation of the often discussed supersymmetry model, according to which the lightest particle, with a new nontrivial supersymmetric quantum number, would be stable and thus survive from the Big Bang. Should this or something similar be so, we have the exciting possibility that by using the methods suggested for neutrino recoil detection we could also observe the dark matter in the laboratory.⁸

The suggestion to use nuclear recoil detection for dark matter was all the more interesting because, surprisingly, the first estimates for some dark-matter candidates gave interaction rates higher than one would even have for neutrinos near a big reactor. To understand how this can happen, note that the dark-matter flux—if it exists—might be substantial. Given in terms of the unknown mass of the dark-matter particle expressed in GeV, the flux is

$$(\text{number of particles/cm}^3) \times (\text{velocity}) \\ \approx (1.2/\text{mass}) \times (10^7/\text{cm}^2 \text{ sec})$$

The particle velocity has been assumed to be $10^{-3}c$, or 3×10^7 cm/sec, a value typical of most objects in the galaxy, and the number density follows from the mass density found by modeling the rotation curves for spiral galaxies, which gives about 0.4 GeV/cm^3 in our Galactic neighborhood. After the flux, the next ingredient in a rate estimate is the cross section of the dark-matter particle on the nuclei of the detector. Here there is an important distinction between those dark-matter candidates that interact coherently with the nuclei of the detector and those that do not. For those that interact coherently, like a conventional but massive neutrino or the hypothetical s neutrino of supersymmetry, there will be a factor like the N^2 in equation 2. The N^2 -like factor, combined with the energy E (which is about equal to the mass of the dark-matter particle when that particle is heavy), leads to interaction rates as high as thousands per kg-day in some cases. For non-coherently interacting particles, on the other hand—the photino of supersymmetry, for example—the rates come out more like 1 per kg-day or less.

From the point of view of instrumentation an attractive aspect of massive particle dark matter is that the slow heavy particle would tend to produce a larger recoil than neutrinos would. This is simply kinematical and independent of the nature of the interaction: A particle of many GeV in mass with the assumed velocity of $10^{-3}c$ has more momentum it can transfer to the target nucleus than does a relativistic neutrino of a few MeV. Thus the dark-matter search, in addition to presenting the possibility of finding most of the mass in the universe, poses, instrumentally speaking, an attractive station on

the way down to very small recoils. (Figure 2 shows a simulation of the recoil spectrum.)

Double beta decay and ν - e scattering

There have also been interesting ideas for improving or extending existing techniques by using the greater sensitivity or resolution that low temperatures offer. In double-beta-decay studies, for example, one looks for the very rare nuclear transformation involving two charges $A_Z \rightarrow A_{Z+2}ee(\nu\nu)$, with or without the two neutrinos. (The monitored nuclei can have lifetimes on the order of 10^{24} and more years.) In particular, the neutrinoless branch is potentially very significant for particle physics and cosmology, in that it would show lepton-number violation: Two leptons (the electrons) come out, but no antileptons. This branch, according to theory, would also simultaneously show a mass for the Majorana (self-conjugate) neutrino, presumably present in the intermediate state—*itself* a dark-matter possibility. The sought-for energy deposit from the two electrons is typically around 1 MeV. Here the increased energy resolution per unit mass of a cold detector offers the possibility of handling more material and hence obtaining sensitivity to nuclei that have longer lifetimes.⁹ This is likely to be one of the first applications of a true low-temperature technique, and there are interesting possibilities connected with the fact that some double-beta nuclei, such as ^{100}Mo , are also superconductors.

The detection of solar neutrinos by scattering on electrons is conventionally possible only for the highest-energy neutrinos in the solar flux. Low-temperature techniques, with their sensitivity to the much smaller energy of the scattered electron, may be able to make the more intense, low-energy end of the solar-neutrino spectrum accessible.¹⁰ Numerous other low-temperature applications have been considered, such as to the inverse beta reaction of indium with solar neutrinos or to superconducting high-energy-particle detector elements for applications where radiation hardness is important.¹

First results on dark matter

Predictably, the first consequence of the cryogenically inspired proposal to look for dark matter in the laboratory was that the “competition” (instrumentally speaking) got into the act. The relatively large recoils and, in some extreme cases, high interaction rates proposed for the massive dark-matter particles implied that double-beta-decay experiments that are already running should be able to say something about the dark-matter question. And indeed these experiments, which are based on essentially conventional but very well-shielded germanium detectors, have given the first laboratory constraints on dark matter.¹¹ Further work with instruments of this kind, including a detector using the lighter and thus more highly recoiling silicon (the mass is in the denominator in equation 3), is steadily setting better limits for the future cryogenic detectors to shoot at. Figure 3 summarizes some recent germanium results. This first round of experiments with semiconducting detectors was inspired by the high rates and recoils that would arise under the simplest

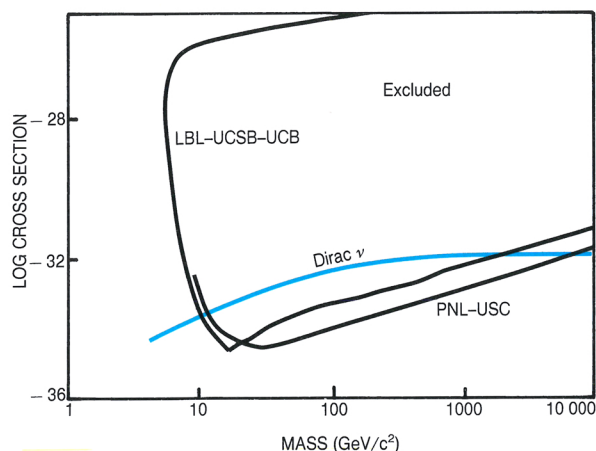
hypothesis, that the dark-matter particle is something like a conventional but massive neutrino coupling to the weak charge of ordinary matter. The s neutrino of supersymmetry and the heavy Dirac (ordinary) neutrino are two particles of this kind.

Information on such particles arrived from a totally different quarter last year when the Large Electron Positron collider at CERN came on line and delivered accurate results on the width of the weak intermediate boson Z^0 . A neutrino, or an object closely related to it, couples to matter via a virtual Z^0 . For a *real* Z^0 , therefore, there is then a decay into a pair of the dark-matter objects, mass allowing, just as there is a decay into the ordinary light neutrino. If the heavy neutrino or s neutrino exists and if a pair does not have more mass than a Z^0 (90 GeV), then these new objects should have given the Z^0 an extra decay channel and hence some extra linewidth. But the LEP results find the Z^0 width to be distressingly conventional. So if the new object has the most standard couplings, anything lighter than around 45 GeV is ruled out, closing off most of the upper left side of figure 3. These arguments are all in the context of the simplest model, and such things as couplings to hypothetical heavier Z 's are of course not entirely ruled out.

In any case, as far as dark-matter detection is concerned, it is certainly appropriate to adopt a strictly observational standpoint and not pay too much attention to theoretical models. The LEP results have, however, tended to focus attention on the next supersymmetric candidate, the photino, a self-conjugate derivative of the photon. The photino would not affect the Z^0 . Most theories predict that it should not have coherent interactions, and so this leads to interaction rates of only a few per kg-day or less. The same consideration applies to similar self-conjugate (Majorana) objects, and we may expect a strong effort in the upcoming years to reach the level of sensitivity and background suppression needed for their detection.

Low-temperature devices

The great potential sensitivity of low-temperature techniques, which suggests that some of the ambitious proposals mentioned above might be feasible, may be expressed through many different kinds of instrumentation. In the superconducting grain method mentioned at the beginning of this article and first proposed for the detection of reaction 1, the deposited energy heats and flips the grain to the normal state. The flip is then read out through the signal given by the disappearance of the Meissner effect—that is, by the collapse of the applied magnetic field around the grain. Single flips of grains that are not too small (some tens of microns) can be seen with conventional sensitive electronics, and with a superconducting quantum interference device, or SQUID, sensor, it has been possible to see flips of rather small grains in relatively large sensitive areas. (See figure 4.) Furthermore, work on single grains has shown that for certain metals the grain does indeed act like a little calorimeter, with a heat capacity determined by the known specific heat of the material.¹² The main difficulty with the



Experimental limits on the detection of possible dark-matter particles with germanium detectors. Data from two groups—a collaboration among researchers at Lawrence Berkeley Laboratory and the University of California at Santa Barbara and Berkeley, and a team from Pacific Northwest Laboratory and the University of South Carolina—define the “excluded” region of this mass–cross section diagram. A Caltech–University of Neuchâtel–Paul Scherrer Institute collaboration has obtained similar data. The blue line labeled “Dirac ν ” would be expected for a standard massive neutrino. (Adapted from P. D. Barnes Jr et al., *Low Background Underground Facilities for the Direct Detection of Dark Matter*, U. Calif., Santa Barbara, 1990.) **Figure 3**

method seems to be preparing the material with sufficient uniformity. To have a substantial mass, a multitude of grains, all with very similar properties, must be fabricated. Photolithographic methods have considerably improved fabrication results.

In a system consisting of many small elements such as superconducting grains, the primary energy deposit is contained in a small volume and there is the potential for great sensitivity (which is balanced against the problem of nonuniformity). In another approach, one may simply take a relatively large sample and measure its temperature rise with a sensitive thermometer. The temperature rise of a solid is governed by its heat capacity C , which is typically given by

$$C = \gamma T + \beta T^3 \quad (4)$$

The first term is due to conduction electrons and the second to lattice vibrations, or phonons. For a superconductor the first term is replaced by a quantity involving the Bardeen–Cooper–Schrieffer factor $\exp[-(\text{const})T_c/T]$ and so is very small well below T_c . In a dielectric the first term is absent entirely. The rapid decrease of the T^3 term at low temperatures then leads to very small heat capacities, particularly if one chooses a material with a high Debye temperature (small β). For instance, the Debye formula implies that 1 keV deposited in 1 kilogram of silicon at 20 mK produces a temperature jump of 50 nanokelvin.

In this line of development the key element is the thermometer. It should be well matched to the absorber so

as not to reflect the excitations coming from the material, and should itself have a negligible heat capacity. Furthermore, because it will usually involve a current of some kind, self-heating effects need to be under control.

For example, a recent experiment at the Technical University of Munich used a superconducting strip thermometer on a sapphire crystal.¹³ With this kind of thermometer, one operates the detector at the transition temperature of a superconductor, in this case iridium at 120 mK. The strip, a film of micron dimensions evaporated onto the dielectric crystal, goes from zero resistance to around an ohm over a few millikelvin, and carries a current of a few microamps. Combined with a SQUID to sense the great variation of resistance with temperature, the strip makes a sensitive thermometer. The device was a quite substantial 280 grams and achieved a resolution of 1% for 5-MeV alpha particles. The measuring accuracy of the strip itself corresponded to 50 nanokelvin. If valid, the above extrapolation to silicon at 20 mK, which also yields a jump of 50 nK, puts us in the range of what is needed to detect some massive dark-matter particles or many-MeV neutrinos. The system, however, is constrained to operate at the transition temperature of some suitable superconductor, and attempts to go down to the regime of tens of millikelvin will involve finding strip materials suitable for these lower temperatures.

Another kind of thermometer that has been under extensive study is the thermistor, which has been used as a radiometer for studying the cosmic microwave background, among other things. In a thermistor a large variation of electrical resistance with temperature is produced by doping a dielectric with donors or acceptors, often using neutron irradiation. This is done to such an extent that the material is very close to becoming a metal, and so is very sensitive to any agitation of the charge carriers. The thermistor can either be doped into the calorimeter material itself or be glued onto it. Workers with thermistors have, in small (10 microgram) devices, produced the best energy resolution to date, 6 eV on a 6-keV gamma.¹⁴

A nice result with a thermistor has given a direct observation of nuclear recoil. In a test, some atoms of an alpha source being used to irradiate a thermistor accidentally implanted themselves in the device. Due to the thermistor's very high energy resolution, the alpha peaks were now found to be split into two: Events originating inside the thermistor were shifted up slightly by the energy of the recoil from the alpha decay, while those from outside showed the alpha energy alone.¹⁵

These and other methods in which a simple temperature rise is established may be classified as “equilibrium” methods; that is, it is assumed that the deposited energy produces thermal equilibrium, at which a new temperature is measured. If the energy is well equilibrated, the signal is proportional to the energy deposit and independent of the location of the event.

Nonequilibrium devices

It is notorious that equilibrium is often slow and difficult to achieve at low temperatures. Various parts of the

apparatus, or even subsystems of a given material such as spins, phonons and so forth, may take a long time to come into thermal equilibrium among themselves and with the rest of the system. Indeed the slowness of low-temperature devices is often a point at issue in an experimental arrangement, particularly with regard to noise and background.

In "nonequilibrium" devices we try to turn this decoupling to our advantage. Note that our original energy deposit, even if it is as low as 1 eV, is always rather "hot": In "natural" $k = 1$ units, after all, 1 eV = 12 000 K. The slow equilibration means there will be a relatively long phase after the event, before the energy is finally degraded to the ambient temperature or lost to the cryostat, during which "hot, high-energy" excitations are present. We then try to detect these excitations directly, with the prospect of a relatively high energy on the sensor and, if we can catch the "first burst," the possibility of sharp spatial and temporal resolution.

Estimating the number of these excitations gives another way of appreciating the significance of low temperatures. In a superconductor, for example, Cooper pairs break to create "quasiparticles." This costs an energy per pair on the order of the superconductor gap, or T_c —say, 10^{-4} eV for common superconductors. Thus a 1-eV primary energy deposit could yield 10^4 excitations. By contrast, when one creates electron-hole pairs with an energy input of around 1 eV in a semiconductor detector, one gets on the order of only one excitation. For a reliable detection scheme we desire a large number of excitations in order that the inherent fluctuations $\sqrt{N}$ will be small and so that we might get the canonical factor of ten for comfort. Hence for energy deposits much below some keV, low-temperature devices seem unavoidable. Alternatively, if it became possible to collect and count quasiparticles a few at a time, then the $\sqrt{N}$ argument would imply an energy resolution of microvolts in a low- T_c superconductor such as tungsten ($T_c = 15$ mK).

The slow equilibration of energy is connected with the fact that excitations often have long lifetimes and travel ballistically, without collisions. A low-frequency phonon in a pure material at low temperature, where there are no impurities, defects or other phonons to bump into, can have a mean free path of meters. Thus in analogy to the cloud chamber, spark chamber and similar devices that detect particles with relatively high energies, one can imagine a phonon or quasiparticle "chamber," consisting of a large piece of pure material at low temperature, its surface plastered with excitation detectors that locate and give the energy of each event. The excitations in question could be phonons in a crystal, quasiparticles (broken Cooper pairs) in a superconductor, rotons in liquid helium, the excitations of superfluid helium-3 or other things to come.¹⁶

This is a highly ambitious avenue. The energies of eV or keV that seemed small enough when localized in a micron-sized grain would now be spread out over a large collecting surface. On the other hand, such a "chamber" could be a large, simple piece of material with low and well-understood background. Geometric information, as from phonon focusing or time-of-flight information, would help to locate events in the "chamber." This location information would be particularly valuable because after

the detecting material has been cleaned and purified, the worst backgrounds are to be anticipated on the surface, and their locations can be used to reject them.

The question now becomes the choice of the sensor for the excitation. Ideally, we would like a sensor that can detect a single phonon, quasiparticle, roton and so on. While this sensitivity seems remote at the moment—we are talking meV at the most—there have been a number of ingenious proposals ranging from the employment of relatively familiar devices such as tunnel junctions or superconducting strips (used in this case as impulsive sensors) to new and novel things such as roton detectors.

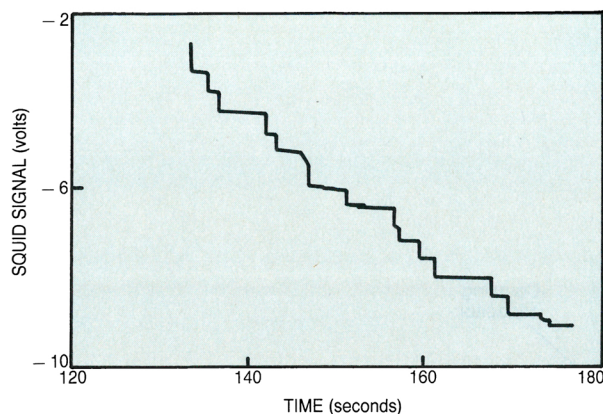
The superconducting tunnel junction, which is potentially sensitive to single excitations, is among the most studied devices in the field. The operating mechanism is the tunneling of quasiparticles through an insulating barrier, but the device can also be sensitive to phonons because a phonon entering the junction can break up Cooper pairs. Thus junctions are used for the detection of both phonons in dielectrics and excitations in superconductors. The device is very sensitive, but it is small and its fabrication is nontrivial. Various tunnel junction projects are concerned with increasing area coverage, retaining low noise, matching to the detector and so forth. In one project one of the two films of the classic junction is replaced by a massive superconducting crystal, so that the junction becomes the detector volume itself (figure 1). In related work, a "quasiparticle multiplier," in which the quasiparticles multiply by going downhill into a material of lower gap, has been proposed. Schemes where the quasiparticles are trapped before being measured in the tunnel junction aim at collecting excitations over an area much larger than that of the small junction.¹⁷

Strips of superconductor can also be employed in an impulsive mode, as a detector for phonon bursts. In one scheme thin strips of titanium are laid down in a long meander pattern on a silicon wafer.¹⁸ The circuit carries a current but is held nonresistive, just below the superconducting transition (not in the middle of the transition, as for the strip thermometer with its proportional response). When the phonons deliver enough energy to some point on the strip it is driven normal, and the resulting resistive behavior is registered. Plans to use tungsten, with its low T_c of 15 mK, could produce strips sensitive to single phonons.

Liquid helium, usually thought of as the coolant in cryogenic work, can also be considered for the detector.¹⁹ Single phonons may be able to eject atoms from a film of helium. In another proposal, the primary energy deposit in a bath of pure helium generates rotons—the basic excitations in superfluid helium—which then knock atoms off the surface of the bath. These in turn are accelerated and captured by a silicon surface. Unfortunately, because helium has a neutron number N of only 2, the great enhancement via equation 2 for nuclear scattering is gone, so the application is to the recoil electron from ν -e scattering. An attractive aspect of this scheme is the great purity of liquid helium.

A low-energy frontier?

Interaction rate figures like 1 per kg-day make it doubly evident that background and its suppression are central to the question of low-energy, low-rate detection. This leads



'Flips' of superconducting grains of tin at 3.1 K to the normal state upon absorbing 140-keV gamma rays. Each step on this readout from a SQUID represents a change in the state of an individual 6-micron grain. (Adapted from A. Da Silva, M. Le Gros, B. G. Turrell, A. Kotlicki, A. K. Drukier, in workshop II of ref. 1, p. 417.) **Figure 4**

to novel technological problems in addition to the sensor fabrication issues discussed above. Low-background cryostats are necessary, and so materials with simultaneously good thermal, mechanical and radiological properties must be found. Sensing materials must be evaluated with respect to their purity, and sensing schemes with respect to their ability to help suppress the background. A point of importance here is that almost all backgrounds interact primarily with the electrons in the detector, while for dark matter and neutrino-nucleus scattering the sought-for event is nuclear recoil. Thus separation of the two would be of great value. A group at Berkeley's Center for Particle Astrophysics has reported on a hybrid device that detects ionization and temperature rise separately but simultaneously²⁰ (see figure 5).

The knowledge accumulated in the low-counting-rate community, where ever lower levels are being reached, will be of great help in mastering the background problem. Very recent results²¹ have been announced at the impressive, if perhaps not astonishing, level of 0.1 counts/kg-year-keV in a double-beta-decay germanium experiment, and plans are on the drawing boards for improvements. True, these numbers are for energies around 2 MeV, and it is a familiar fact that background gets worse as the energy threshold is lowered. Nevertheless such numbers are encouraging for the first cryogenic dark-matter searches, which aim at about 1 count/kg-day-keV for recoils in the keV range.

In addition to the background issue, there are also challenges in connection with low-temperature electronics, particularly for large systems involving many readout channels, which seem inevitable for massive systems. SQUIDs are exquisitely sensitive, but at the moment are also expensive and delicate to operate. Will large arrays of easy-to-use and affordable SQUIDs or other cold electronics become available in the not-too-distant future?

Beyond such technological questions, the ultimate development of the low-temperature detection of low energies poses some amusing questions of basic physics. Work in the field, which generally hasn't gone below dilution-refrigerator temperatures, in the vicinity of 10 mK, is far from plumbing the depths of true low-low-temperature physics, which gets into micro- if not

nanokelvins. If a formula like equation 4 with $\gamma = 0$ is naively extrapolated to these frontiers, one arrives at startling results where practically nothing will heat up nearly everything. Blithely continuing our earlier extrapolations with the T^3 law, and lowering the operating temperature from 20 millikelvin to 20 microkelvin supplies another factor of 10^{-9} . Now our 1-keV energy deposit produces a 50-nanokelvin temperature jump in a megaton of silicon!

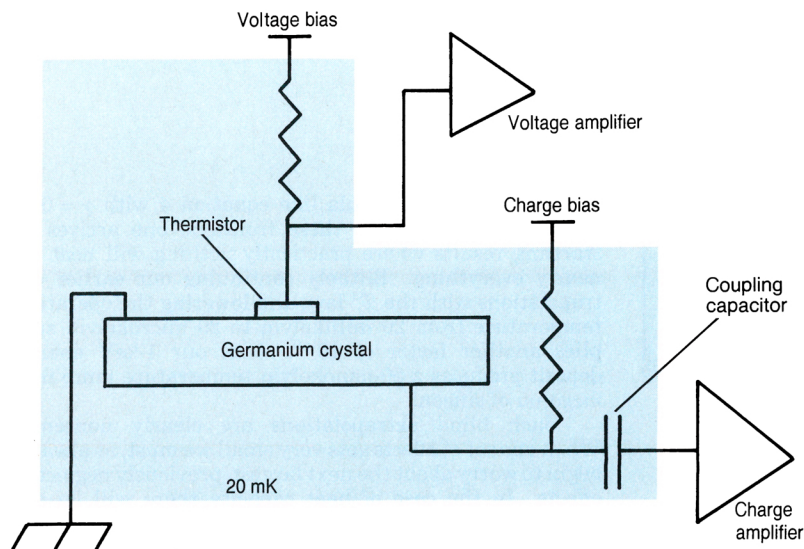
Such blind extrapolations are clearly nonsense. When one set of effects gets very small we must, as always, begin to worry about the next largest, previously neglected effects. In the case of heat capacity there will be the effects of strains and defects, spins (which might themselves be used as a sensor²²), surface effects and so forth.

Nevertheless, given the variety of possible ideas and systems, it is not clear that *all* extrapolations are nonsense. Is there an indefinite scale of "room at the bottom," much as there has always been "room at the top" at high energy? Do we need this room? Below 1 mK, the 1-eV recoil from the abundant solar pp-cycle neutrinos becomes a veritable bomb, producing 10^6 10-mK excitations. With a sensor for these excitations, detection of solar neutrinos and rejection of background would be a piece of cake—always assuming we are not swamped by dark-matter signals, of course. Or, with a megaton of superconducting sensors, we could detect neutrino bursts from galaxies at megaparsec distances. This could bring enough galaxies into range that we would have many supernovas a year to look at in neutrinos instead of the meager one or two per century from the Milky Way. The liquid helium plants of HERA or the SSC, with their many tens of kilowatts of low-temperature cooling power, should handle the cool-down easily.

And then there is the question of the cosmic neutrino background, the Big Bang neutrinos, which should be present with a temperature of about 1.9 K and a density of about 300 per cubic centimeter. Here there are as yet no remotely practicable ideas for detection, although there has been no lack of imagination employed on the subject. If there ever is a solution, it will very probably involve cryogenic techniques.²³

Most of the ideas are still in the speculative or in the R&D phase, and of course the effort and investment have been relatively small. However, the basic physics makes sense, and there is a small but enthusiastic community working in the field. In the US and Canada groups at the University of South Carolina, the University of California at Santa Barbara and Berkeley, Stanford and Caltech are working on low-temperature as well as semiconductor dark-matter detection. Meanwhile, progress on grain preparation by lithography has been made in Vancouver, and liquid helium as a detector is under study at Brown. The Center for Particle Astrophysics, the NSF-funded center for dark-matter studies at Berkeley, where cryogenic work is a key activity, has played an important role in stimulating efforts on these and other subjects related to dark matter.

In Europe, the Munich area, with Technical University and Max Planck groups, is a major center of low-temperature work, while in the UK, in addition to the tunnel junction work at Oxford, there is the UK dark-matter project, which is preparing an installation in the



Germanium ionization detector shown by this schematic also measures temperature rise by means of the attached thermistor. The portion of the circuit in the shaded area is at 20 mK. (Adapted from ref. 20.) **Figure 5**

Boulby mine. In France, where the work on superconducting grains started in Paris many years ago, there are also groups at Annecy and Orsay and an effort on crystal bolometers. In Switzerland, in addition to tunnel junction work at Neuchâtel and the Paul Scherrer Institute, a University of Berne group is studying superconducting grains in a test beam at the Scherrer Institute. The Milan University National Institute group, traditionally strong in low-background studies, is well advanced with a low-counting dilution refrigerator in the large laboratory beneath the Gran Sasso near Rome. Recently, in an important development, the Italian government approved new halls in the Gran Sasso lab, one of which is to be laid out for cryogenics. In Japan, a Kobe University-Chiba group has carried out tests with tin grains.

Present work in the field, often involving reconvered particle physicists looking for leaks and struggling with the ABCs of low temperature, is of course far from delving into ultimate issues, but the question of the future development is certainly intriguing. If progress continues, it may not be an exaggeration to say we are witnessing the birth of a "low-energy frontier" of fundamental physics, where big things are hunted with little means.

References

1. The theme of this article was the topic of three workshops, whose proceedings contain extensive discussions and references: K. Pretzl, N. Schmitz, L. Stodolsky, eds., *Proc. Wksp. on Low Temperature Detectors for Neutrinos and Dark Matter*, Springer-Verlag, New York (1987); L. Gonzalez-Mestres, D. Perret-Gallix, *Proc. Wksp. on Low Temperature Detectors for Neutrinos and Dark Matter II*, Editions Frontières, Gif-sur-Yvette, France (1988); L. Brogiato, D. V. Camin, E. Fiorini, eds., *Proc. Wksp. on Low Temperature Detectors for Neutrinos and Dark Matter III*, Editions Frontières, Gif-sur-Yvette, France (1990).
2. S. Simon, *Nature* **135**, 763 (1935). A. Goetz, *Phys. Rev.* **55**, 1271 (1939). H. Andrews, R. D. Fowler, M. C. Williams, *Phys. Rev.* **76**, 154 (1949).
3. D. Z. Freedman, *Phys. Rev. D* **9**, 1389 (1974).
4. A. K. Drukier, L. Stodolsky, *Phys. Rev. D* **30**, 2295 (1984).
5. C. Alviléz, G. Marx, B. Fuenes, *Phys. Rev. D* **23**, 1116 (1981). L. M. Krauss, S. Glashow, D. Schramm, *Nature* **310**, 191 (1984). See also figure 11 of ref. 4.
6. M. Goodman, E. Witten, *Phys. Rev. D* **31**, 309 (1985). I. Wasserman, *Phys. Rev. D* **33**, 2071 (1986).
7. For some references on dark matter, see V. Trimble, *Annu. Rev. Astron. Astrophys.* **25**, 425 (1987); T. S. van Albada, R. Sancisi, *Philos. Trans. R. Soc. Lond., Ser. A* **320**, 447 (1986); A. De Rújula, D. Nanopoulos, P. Shaver, eds., *A Unified View of the Micro- and Macro-Cosmos*, World Scientific, Singapore (1987); M. Turner, "Dark Matter in the Universe," *Proc. Nobel Symp.* 79, Nobel Committee, Stockholm.
8. See the review by J. Primack, D. Seckel, B. Sadoulet, *Annu. Rev. Nucl. Part. Sci.* **38**, 751 (1989).
9. E. Fiorini, T. O. Ninikoski, *Nucl. Instrum. Methods* **224**, 83 (1984).
10. B. Cabrera, L. Krauss, F. Wilczek, *Phys. Rev. Lett.* **55**, 25 (1984).
11. S. P. Ahlen, F. T. Avignone III, R. L. Brodzinski, A. K. Drukier, G. Gelmini, D. N. Spergel, *Phys. Lett. B* **195**, 603 (1987). For silicon detectors, see D. O. Caldwell *et al.*, *Phys. Rev. Lett.* **65**, 1305 (1990).
12. For early work on superconducting grains, see A. K. Drukier, C. Valette, *Nucl. Instrum. Methods* **105**, 285 (1972); D. Hueber, C. Valette, G. Waysand, *Nucl. Instrum. Methods* **167**, 201 (1979). For recent work see the workshops in ref. 1. For studies of single grains, see M. Frank, P. Freund, J. Gebauer, K. Pretzl, A. Singaas, L. Stodolsky, *Nucl. Instrum. Methods A* **287**, 583 (1990); *Phys. Lett. B* **230**, 159 (1989).
13. W. Seidel, G. Forster, W. Christen, F. von Feilitzsch, H. Göbel, F. Pröbst, R. L. Mössbauer, *Phys. Lett. B* **236**, 483 (1990).
14. D. McCammon, in workshop III of ref. 1, p. 213, and private communication.
15. A. Alessandrello, D. V. Camin, E. Fiorini, A. Giuliani, *Phys. Lett. B* **202**, 611 (1988).
16. For ^3He , see G. R. Pickett, in workshop II of ref. 1, p. 377B.
17. D. J. Goldie, N. E. Booth, C. Patel, G. L. Salmon, *Phys. Rev. Lett.* **64**, 954 (1990). T. Peterreins, F. Pröbst, F. von Feilitzsch, R. L. Mössbauer, H. Kraus, *Phys. Lett. B* **202**, 161 (1988). D. Twerenbold, A. Zehnder, *J. Appl. Phys.* **61**, 1 (1987).
18. B. A. Young, B. Cabrera, A. T. Lee, *Phys. Rev. Lett.* **64**, 2795 (1990).
19. R. E. Lanou, H. J. Maris, G. M. Seidel, *Phys. Rev. Lett.* **58**, 2498 (1987). H. Kinder, in workshop III of ref. 1, p. 305.
20. A. Cummings *et al.*, "Performance of a 60 Gram Cryogenic Detector," Center for Particle Astrophysics, U. Calif., Berkeley (1990).
21. F. T. Avignone III *et al.*, *Phys. Lett. B* **256**, 559 (1991).
22. M. Bühler, E. Umlauf, *Europhys. Lett.* **5**, 297 (1988).
23. For a survey of these issues, see L. Stodolsky, A. Bottino, P. Monacelli, eds., *TAUP '89*, Editions Frontières, Gif-sur-Yvette, France (1989), p. 2. ■