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New Detectors for Neutrinos and Dark Matter

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New detectors for neutrinos and dark matter

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Hypothetical particles in the GeV mass range and with typical Galactic velocity $10^{-3}\,c$ would have MeV range momentum, similar to that of solar or supernova neutrinos. Thus elastic collisions with target nuclei would in each case give keV range nuclear recoils. There would also be a cross-section enhancement arising from full or partial coherence over the constituent nucleons. Detectors for these low energy nuclear recoils can be based on ionization, scintillation or low temperature phonon techniques. Radioactive background in the detector materials provides the main obstacle to detecting low event rates and significant effort is now being made to develop more advanced ideas which will distinguish the nuclear recoil events from background. Examples are simultaneous measurement of ionization and phonon energy in semiconductors, and photon timing or wavelength filtering in scintillators. Several groups are actively constructing underground dark matter detectors with targets in the 1–100 kg range.

Solar and supernova neutrino detectors based on coherent scattering would have much lower target masses (by factors 20–100) than conventional detectors but would still require a substantial scale-up of these new techniques. Experiments with reactor neutrinos will provide a first step in verifying coherent neutrino scattering. Further scale-up to allow extra-galactic neutrino detection is feasible in principle and a possible challenge for the 21st century. Macroscopic coherent detection of the relic neutrino background may also become possible with foreseeable new technology.

1. Introduction: detection by elastic scattering from nuclei

We discuss progress towards new detectors for astrophysical neutrinos and hypothetical dark matter particles, based on elastic scattering from nuclei. The new detectors aim to detect the resulting low energy nuclear recoil events and to distinguish these from radioactive background. The techniques also benefit from full or partial coherence of the nuclear scattering, the scattering amplitude being summed over the constituent nucleons. In the case of neutrino interactions this can result in a large gain in cross section and hence a corresponding reduction in target mass compared with neutrino detectors based on inelastic interactions. For interactions which depend on the net nuclear spin, the cross section would not be enhanced by the coherence.

A numerical coincidence allows these nuclear scattering techniques to be considered both for MeV range neutrinos and for galactic dark matter in the form of weakly interacting massive particles. Particles trapped in the galaxy would necessarily have velocities similar to that of visible matter, i.e. an r.m.s. velocity in the region $0.001c$, so that GeV range masses will have MeV range momenta. Table 1

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Table 1. *Typical nuclear recoil energies for Galactic dark matter particles, supernova neutrinos and solar neutrinos*

	energy MeV	momentum MeV c^{-1}	nuclear recoil energy (keV) for $A = 20$	$A = 50$	$A = 100$	$A = 200$
dark matter						
mass 20 GeV	0.01	20	5	4	3	2
mass 200 GeV	0.1	200	16	32	44	50
supernova	10	10	5	2	1	0.5
	30	30	45	18	9	4.5
solar	0.2	0.2	0.002	0.0008	0.0004	0.0002
	1	1	0.05	0.02	0.01	0.005
	10	10	5	2	1	0.5

shows typical values of momentum and nuclear recoil energy for the elastic scattering of hypothetical dark matter particles with GeV masses, supernova and solar neutrinos, and also reactor neutrinos. Recoil energies in the keV range result for dark matter particles and supernova neutrinos. Reactor neutrinos give recoil energies in the 0.1–1 keV range, and the broad momentum range of solar neutrinos results in nuclear recoil energies extending down to the eV range.

A coherent gain in cross section results when the wavelength (divided by 2π) of the momentum transfer is comparable with, or exceeds, the nuclear radius, so that many or all of the nucleons contribute coherently. For target nuclei $A = 20$–200, the nuclear radius is $r \approx 4$–8×10^{-13} cm, or *ca.* 50–25 MeV^{-1}. Thus for momentum transfer $q \ll 25$ MeV the cross section increases as the square of the number of participating nucleons. For larger momentum transfer the nuclear form factor $F(qr)$ becomes less than 1 offsetting the coherent gain. Eventually, for sufficiently large qr, the cross section drops below even the single particle cross section.

2. Detector requirements and principles

It is immediately evident from the above that the crucial parameter limiting sensitivity is the energy threshold of the detector. This needs to be as low as possible, firstly to register the highest possible proportion of events, and secondly to ensure the maximum coherent gain. To illustrate this quantitatively, we show in figures 1 and 2 the total number of detected nuclear recoil events as a function of detector energy threshold and target nucleus, for different types of astrophysical particle source.

For dark matter particles, or supernova neutrinos, detector thresholds less than 10–30 keV are needed, and preferably *ca.* 1 keV. For solar neutrinos thresholds less than 0.1 keV are needed. These basic requirements have been known since 1984, and detector development has proceeded along the paths discussed below.

(*a*) *Solid state ionization detectors*

Semiconducting detectors, principally using Ge as the target, have been in operation underground for many years as double beta decay experiments. Although double beta decay searches involve the 1–2 MeV region, the same Ge detectors can be used as low energy nuclear recoil detectors. The recoiling Ge atoms have, by the standard Lindhard model (confirmed by measurements), an ionization efficiency *ca.*

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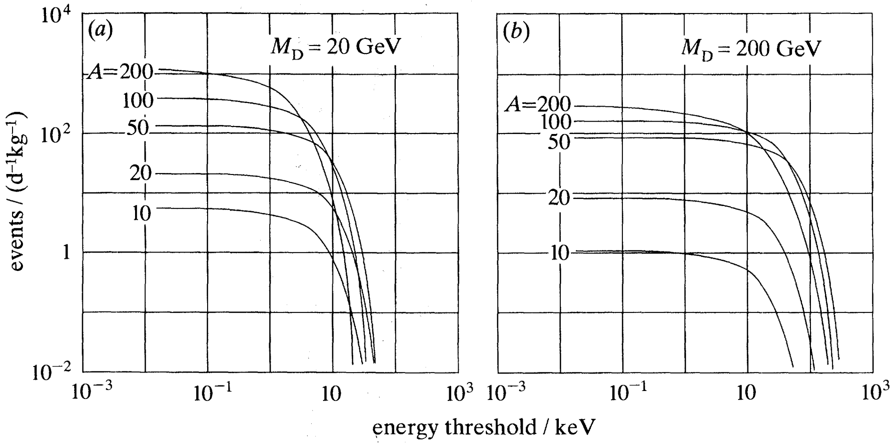

Figure 1. Total event rate versus energy detection threshold for hypothetical weakly interacting (spin independent) dark matter particles with mass (*a*) 20 GeV and (*b*) 200 GeV.

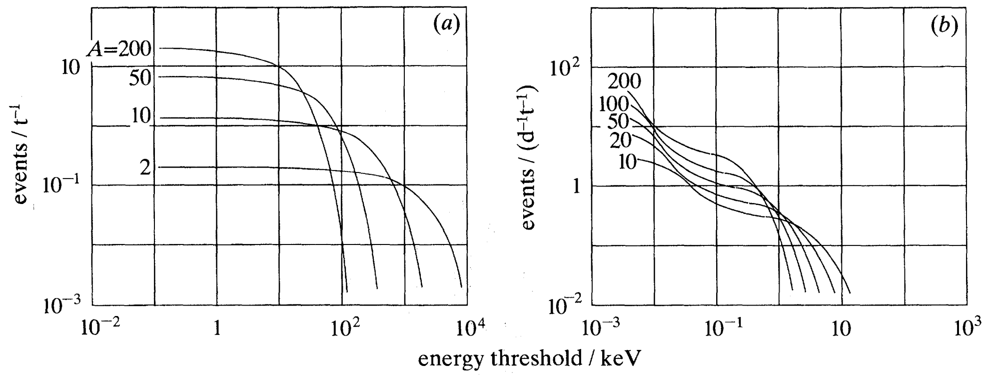

Figure 2. Total event rate versus energy detection threshold for (*a*) standard solar model neutrino spectrum; (*b*) typical supernova neutrino burst at distance 10 kpc.

20–30 % compared with electron recoil in the energy range 1–100 keV. Thus the Ge energy threshold *ca.* 4 keV corresponds to about 16 keV nuclear recoil. Current detectors use Ge crystals with individual masses up to a few kg and are usually operated at liquid nitrogen temperature. Comparable performance as a low energy detector can be achieved with silicon, which can achieve energy thresholds *ca.* 1–2 keV and lower (corresponding to 4–8 keV nuclear recoil) but with smaller individual crystal sizes. Other semiconductor detector development has included the materials GaAs, TlBr and HgI_2, all of which are currently inferior in energy threshold and have additional problems of reliability and cost.

(*b*) *Scintillation detectors* (*crystals or noble liquids*)

Although scintillation detectors – with their basic advantage of large volumes at relatively low cost – are extensively used throughout particle physics, their serious study as low energy nuclear recoil detectors is very recent. This is firstly because low energy threshold at low background is difficult to achieve in scintillator–photomultiplier systems, and secondly because the relative scintillation efficiency for nuclear recoil is only now being studied and measured. Current development work is based principally on sodium iodide, calcium fluoride and noble liquids (in particular xenon and argon). Crystal scintillators have relative efficiencies in the range 10–30 % for recoil of the constituent atoms. The relative scintillation efficiency for Xe in Xe, or Ar in Ar, is still not known at the time of writing, though expected to be greater than 30 %, and measurements via neutron scattering are now in preparation by several groups. Operation at the level of 2–4 detected photons, with optimized light collection, should allow energy thresholds in the region 1–10 keV to be achieved with 1–10 kg targets. Initial detector development is based on photon detection with photomultipliers (*ca.* 20 % quantum efficiency) but future improvements may result from avalanche photodiode devices with *ca.* 100 % quantum efficiency. Because of the relatively low unit cost of scintillating materials, scale-up to the tonne level and higher can be envisaged.

(*c*) *Bolometric or phonon detectors at temperatures below* 1 K

In any material nuclear recoil energy converts to phonon energy with nearly 100 % efficiency. The phonons can either be detected directly or, after thermalization, as a small rise in temperature. The latter technique is known as bolometric detection, and makes use of the low heat capacity of crystalline materials below 100 mK. Typical materials would be LiF, Si, Ge, or CaF_2, with individual crystal masses 1–100 g. Energy depositions in the keV range produce temperature pulses *ca.* 0.1–1 μK, and these can be measured by means of small Ge thermistors or superconducting transition edge detectors on the crystal surface. Direct phonon detection can be achieved by superconducting transition edge or tunnel junction arrays. These techniques have the capability of achieving energy resolutions below 0.1 keV g^{-1}, but the expensive low temperature environment makes scale up to target masses above 1–10 kg potentially more difficult than in the case of ionization and scintillation detectors.

Details of the above detector development programmes can be found in several conference series. For progress on low temperature detectors see conference proceedings by Gonzales-Mestres & Perret-Gallix (1988), Brogiato *et al.* (1990), Booth & Salmon (1992). For progress on ionization and scintillation detectors see conference proceedings by Bottino & Monacelli (1989), Morales *et al.* (1991), Barrow *et al.* (1991). See also Smith & Lewin (1990) and Primak *et al.* (1988), for earlier reviews of detection principles.

3. Discrimination of nuclear recoil from background

The only phenomenon which specifically produces a background of nuclear recoil events is the scattering of MeV range neutrons from the interaction of cosmic ray muons with matter. This background can be eliminated by underground operation or by a sufficiently efficient muon veto.

The principal obstacle to using the above techniques for dark matter or neutrino detection is that of radioactive background. In their simplest forms the detectors produce signal pulses which are similar for nuclear recoil events and electron recoil events (from photons or beta decay). Thus even well-shielded underground detectors still have an irreducible background count rate from radioactive impurities, some intrinsic and others ‘cosmogenic’, induced by cosmic ray interactions. Some of this background may consist of recognizable ‘lines’ of well-defined energy, but the majority of the count rate consists of a Compton scattering continuum rising towards low energies typically as $(\text{energy})^{-1}$. The key criterion is the background count rate in events $\text{keV}^{-1}\ \text{kg}^{-1}\ \text{d}^{-1}$, which we refer to as a differential rate unit (DRU). The best backgrounds so far achieved are for the Ge detectors, which have rates *ca.* 1 DRU below 10 keV falling to below 0.1 DRU at 20 keV. For significant dark matter searches, this needs to be reduced by 2–3 orders of magnitude, for example to *ca.* 0.001 DRU at 10 keV. Even lower backgrounds may be needed for astrophysical neutrino detection.

Although improvements in materials purity can be envisaged in the future, and underground manufacture and storage can reduce the cosmogenic problem, the current view is that it is essential to develop detection systems which will distinguish between nuclear and electron recoil events, rejecting more than 99% of the latter to gain at least a factor 10^2–10^3 in sensitivity.

As an intermediate step towards this, one may use time variations in the signal. For example, to identify a supernova neutrino burst lasting, say, 10 s, it is the statistical fluctuations in background which are important rather than the absolute background. A similar effect is available in dark matter searches, where the orbital motion of the Earth will produce a *ca.* 10% annual modulation in the nuclear recoil signal, with a June maximum. A sufficiently large target mass could then identify this as a significant temporal fluctuation above the statistical fluctuations of the background.

However, considerable development effort is now being devoted to versions of the detectors in §2 which will identify individual nuclear collisions. If this can be done, then, since a shielded underground environment can be created in which the neutron flux is negligible, observation of nuclear recoil events would provide clear evidence of elastic weak interactions from dark matter or neutrinos.

The following indicates the range of ideas which, in principle, might be used for nuclear recoil discrimination, some of which are now under development.

(i) Combination of any two of the three techniques in §2. Owing to the differing relative efficiencies for the various processes, the ratio of the two signals for each event will differ for electron and nuclear recoils. The best example of this is the simultaneous measurement of an ionization signal and a thermal signal in a semiconducting target operated at 10–100 mK (figure 3). The principle has been clearly demonstrated experimentally by the Berkeley-based collaboration in Ge (Schutt *et al.* 1992) and by the U.K. collaboration in Si (Spooner *et al.* 1991). At least a factor 100 discrimination is believed to be possible at a few keV energy threshold, and this is the basis of a major planned dark matter experiment by Berkeley/Stanford/UCSB (Sadoulet 1991; Cabrera *et al.* 1991).

(ii) Use of pulse shape or wavelength differences in scintillators arising from the nuclear and electron collisions stimulating different scintillation mechanisms. Pulse shape discrimination is well known as a means of distinguishing alpha or neutron interactions from photon interactions in the MeV region, where sufficient light is collected to show the pulse shape differences. This is used in both crystal and liquid scintillators. At lower energies the discrimination becomes less effective due to the small number of photons available. In some cases, however, the pulse shape differences are sufficiently large for a likelihood analysis of the photon arrival times to provide discrimination at the level of only a few photons. In liquid xenon, for example, various excitation and recombination processes occur with decay times 3, 27 and 45 ns, and nuclear interactions produce a pulse shape which is distinctively different from that produced by electron recoils from photon interactions (figure 4).

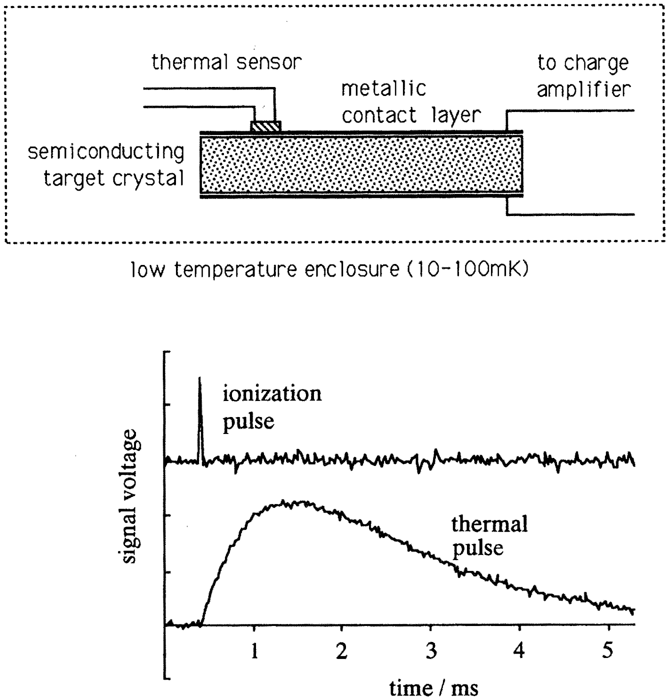

Figure 3. Discrimination of nuclear recoil events by simultaneous measurement of ionization and thermal signals in a low temperature semiconducting target.

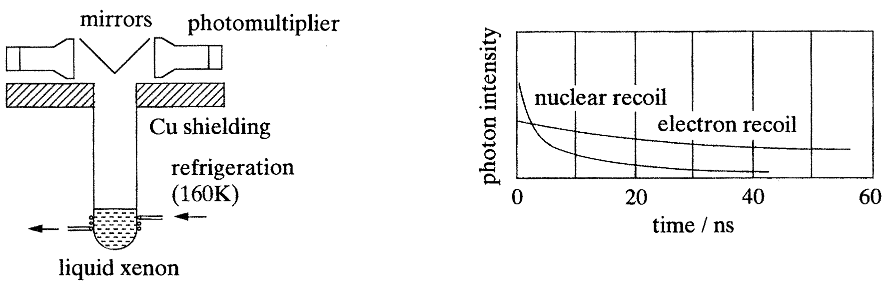

Figure 4. Discrimination of nuclear recoil events by individual photon timing from liquid xenon target.

Detailed analysis (Davies *et al.* 1993) suggests the possibility of factors $10–10^3$ discrimination at the level of 2–6 detected photons, and experiments to verify this (using neutron scattering) are in preparation by several groups.

Differences in wavelength of the scintillation light also offer interesting possibilities. Pure or lightly doped NaI crystals operated at around 100 K emit both UV and visible light, in proportions which differ for nuclear and electron recoils. The UV and visible photons can be distinguished either by filtering or by timing, the UV photons being emitted in a 30 ns pulse, compared with several ms for the visible photons. Again calculations indicate (Spooner & Smith 1993) that at least a factor 100 discrimination should be possible if the low doping levels can be achieved reliably in large crystals and the engineering problems of cooling and operating these at 100 K can be solved effectively (figure 5). A specific dark matter experiment based on this idea is in preparation in the U.K. programme.

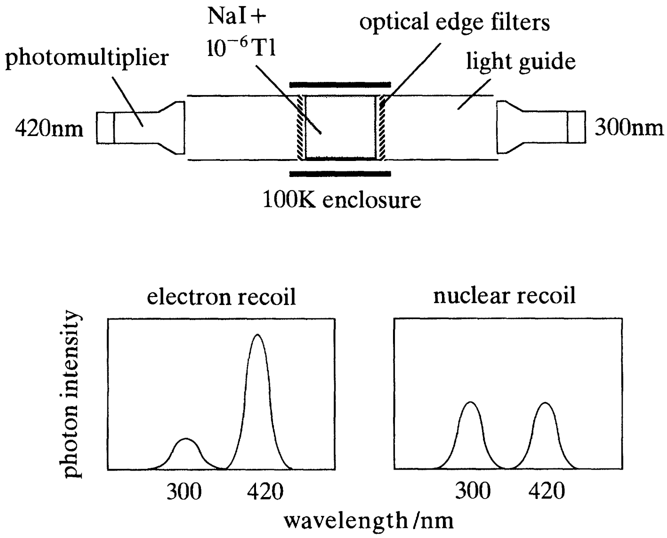

Figure 5. Discrimination of nuclear recoil events by photon wavelength from low-Tl sodium iodide target at reduced temperatures.

(iii) A possible third type of discriminating detector arises from differences in the phonon energy–time distribution from nuclear recoil events. One approach, under development by the Stanford group, is to detect differences in the proportions of ballistic and quasi-diffusive phonons in a pure crystalline material such as silicon (Cabrera *et al.* 1991; Young *et al.* 1992). Another approach, under development by the Oxford group, uses differences in the phonon/quasi-particle ratio in a superconducting target such as niobium (Gaitskell *et al.* 1992). Both ideas require operation at temperatures below 1 K, and possibly below 100 mK for good energy resolution. Tests are in preparation to demonstrate discrimination of nuclear recoil events produced by neutron scattering.

(iv) Among other ideas we note in particular the future possibility of distinguishing electron recoils from nuclear recoils by their much longer range. Electron recoils have a range *ca.* 100 μg cm^{-2} at *ca.* 10 keV and *ca.* 1000 μg cm^{-2} at *ca.* 30 keV, while for nuclear recoils the corresponding ranges are *ca.* 3 μg cm^{-2} and *ca.* 10 μg cm^{-2} (Smith & Lewin 1990). Thus a detector subdivided into layers, filaments or granules on the submicron scale, perhaps using more than one target material, could in principle give a different signal for background events which pass through more than one layer or material. In general, this will require more advanced microfabrication techniques than are currently available, but one proposal which could use existing materials and technology is to use a target consisting of a suspension of crystal scintillator granules (less than 30 nm) in a liquid scintillator of similar refractive index (Spooner *et al.* 1993). Other ideas might be based on the commercial availability of plastic spheres with diameters in the range 10–1000 nm and *ca.* 2% size uniformity.

Multilayer targets with submicron layer thicknesses would also offer, in principle, the additional possibility of sensitivity to the nuclear recoil direction. This would be beneficial in improving background rejection for all applications, since supernova and solar neutrino sources are intrinsically directional, while the dark matter flux incident on the Earth would have a directionality resulting from the motion of the

Earth and Sun through the Galaxy. The 'forward/back ratio' of the nuclear recoils would be about 4:1 (Smith & Lewin 1990).

4. Prospects

Development of detectors based on coherent elastic scattering was proposed in 1984–85 as a means of reducing the target mass needed for astrophysical neutrino detection (Drukier & Stodolsky 1984; Cabrera *et al*. 1985). It was soon realized that significant reductions in limits for weakly interacting dark matter could be achieved with even lower target masses (Goodman & Witten 1985) so that attention became concentrated on dark matter experiments as a first objective (Smith 1986*a*, *b*). Such experiments might then provide a stepping stone to larger targets for neutrino detection.

It can be immediately seen from figure 1 that targets *ca*. 1 kg would register significant daily rates from dark matter collisions with weak interaction strength. For purely spin-dependent interactions, the coherent gain would be lost, but kg quantities would still be sufficient to achieve 0.1–1 events/day given sufficiently good background rejection. In contrast, observation of 100 events from a Galactic supernova neutrino burst would require a 10–40 t target. While this is much less than the typical 1000 t level needed for inelastic processes, it is still a very substantial scale up from current development levels, particularly for those techniques requiring very low temperatures.

Because of this, a number of groups are now actively planning a first stage of experiments to demonstrate coherent scattering of reactor and spallation source neutrinos. Reactor neutrinos have a mean energy of a few MeV and flux *ca*. 10^{13} cm^{-2} s^{-1} giving elastic nuclear collisions at a rate *ca*. 1 d^{-1} for a 1 kg target and 1 keV energy threshold. In addition to demonstrating for the first time the coherent cross-section enhancement, such experiments are given physics interest by the fact that at low energies the shape of the recoil spectrum would be altered (in a precisely calculable way) by a non-zero neutrino magnetic moment. Spallation neutrino sources have a mean neutrino energy which is an order of magnitude higher (giving cross sections a factor 100 higher), but the fluxes are lower than at reactors by a factor *ca*. 10^6, so that required target masses are now *ca*. 1 t or more. Despite this, the spallation source has the unique merit is that it is pulsed (e.g. *ca*. 2 μs every 20 ms) giving an immediate factor *ca*. 10^4 reduction in cosmic ray and radioactive backgrounds. Since these experiments are necessarily near the surface, good neutron shielding combined with an efficient (i.e. greater than 99.9%) muon veto is needed. Monte Carlo studies suggest that the latter may be feasible, and this in turn has led to re-examination of the possibility that dark matter experiments may also be feasible in shallow sites.

Assuming the development of these ideas proceeds as planned on the 1–10 kg scale, what are the prospects for larger astrophysical neutrino detectors? A preliminary assessment of coherent supernova detectors (Smith & Lewin 1992) indicated that the radioactive background requirements appear no more stringent than those required (and believed possible) for dark matter experiments. However, there are several factors which limit the motivation for scale-up to target sizes above the 1 t level. Firstly, in the case of solar neutrinos it is difficult to reach the energy threshold region (0.01–0.1 keV) needed to take advantage of the coherent cross section gain. Secondly, although the energy threshold requirements can be met for a Galactic

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supernova detector, the incentive is reduced by the infrequency of such local (*ca.* 10 kpc) events. Nevertheless, one or two detectors of this type would be of considerable value running in parallel with large 'conventional' detectors (e.g. the SNO heavy water detector) and giving additional data in the event of a local supernova. It should be noted in particular that elastic nuclear scattering is equally sensitive to all three types of neutrino, so that comparison with electron neutrino detectors could provide crucial information on neutrino oscillations. There are plans to link all world supernova detectors to ensure that data are accurately synchronized to extract information on neutrino masses and oscillations (Cline 1991, 1992, 1994). For other recent discussions of conventional supernova detection based on inelastic reactions see, for example, Burrows *et al.* (1992), Totsuka (1992), Seckel *et al.* (1991), Antonioli *et al.* (1991), Steigman (1991), Ryazhskaya *et al.* (1993).

Some interest has been focused on the future possibility of a much larger supernova detector, capable of registering supernovas from a distance *ca.* 4 Mpc at which distance the supernova rate becomes very attractive at *ca.* 1 per year (Becklin 1992; Cline 1991, 1994). For the same number of detected neutrino events (e.g. 100) the target mass increases by a factor *ca.* 10^5, i.e. to *ca.* 10^8 t in the case of single particle interactions and *ca.* 10^6 t for a coherent recoil detector. While this seems at first sight 'out of reach', possibilities can be envisaged for progressive instrumentation for a large volume of natural material such as chalk (Cline *et al.* 1990; Cline 1992) to reach eventually the required 10^8 t, or for automated fabrication of the higher-technology coherent detector (Smith & Lewin 1992). For further speculations on the prospects for large cryogenic neutrino detectors see Stodolsky (1988, 1991).

Finally we note that the detection of the relic neutrino background is not possible by any techniques of the type discussed above since, though interactions of these very low energy neutrinos are coherent over macroscopic target volumes, the resulting energy transfers are too small to be detected by any currently feasible technique. These energy transfers are nevertheless detectable in principle, so this may eventually (perhaps in 20–40 years) be achieved with the aid of future new technology (Smith 1991, 1992).

References

Antonioli, P., Fulgione, W., Galeotti, P. & Panaro, L. 1991 *Nuovo Cimento* C **14**, 631–637.

Barrow, J. D., Mestel, L. & Thomas, P. A. (eds) 1991 *Ann. N.Y. Acad. Sci.* **647**.

Becklin, E. 1992 In *Proc. Conf. Trends in Astroparticle Physics*, pp. 496–503. Santa Monica: World Scientific.

Booth, N. E. & Salmon, G. L. (eds) 1992 *Proc. LTD4 Workshop on Low Temperature Detectors for Neutrinos and Dark Matter*. Editions Frontieres.

Bottino, A. & Monacelli, P. (eds) 1989 *Proc. 1st Int. Workshop on Underground Physics TAUP 89*. Editions Frontieres.

Brogiato, L., Camin, D. V. & Fiorini, E. (eds) 1990 *Proc. LTD3 Workshop on Low Temperature Detectors for Neutrinos and Dark Matter*. Editions Frontieres.

Burrows, A., Klein, D. & Gandhi, R. 1992 *Phys. Rev.* D **45**, 3361–3385.

Cabrera, B., Krauss, L. M. & Wilczek, F. 1985 *Phys. Rev. Lett.* **55**, 25–28.

Cabrera, B. *et al.* 1991 *Nucl. Phys.* B (*Proc. Suppl.*) A **28**, 449–461.

Cline, D. B. 1991 *Ann. N.Y. Acad. Sci.* **647**, 413–424.

Cline, D. B. 1992 In *Proc. Conf. Trends in Astroparticle Physics*, pp. 590–611. Santa Monica: World Scientific.

Cline, D. B. 1994 In *Proc. 4th Int. Workshop on Neutrino Telescopes* (*Venice*). (In the press.)

Cline, D. B., Foshe, T. & Fenyves, E. J. 1990 *Nucl. Phys.* B (*Proc. Suppl.*) A **14**, 348–350.

Davies, G. J., Davies, J. D., Lewin, J. D. & Smith, P. F. 1993 *Phys. Lett.* B. (Submitted.)

Drukier, A. & Stodolsky, L. 1984 *Phys. Rev.* D **30**, 2295–2309.

Gaitskell, R. J., Booth, N. E. & Salmon, G. L. 1992 In *Proc. LTD4 Workshop on Low Temperature Detectors*, pp. 435–444. Editions Frontieres.

Gonzales-Mestres, L. & Perret-Gallix, D. (eds) 1988 *Proc. LTD2 Workshop on Low Temperature Detectors for Neutrinos and Dark Matter*. Editions Frontieres.

Goodman, M. W. & Witten, E. 1985 *Phys. Rev.* D **31**, 3059–3063.

Morales, A. *et al.* (eds) 1991 *Proc. 2nd Int. Workshop on Underground Physics* (*TAUP 91*). *Nucl. Phys.* B (*Proc. Suppl.*) A **28**.

Primak, J. R., Seckel, D. & Sadoulet, B. 1988 *A. Rev. Nucl. Part. Sci.* **38**, 751–807.

Ryazhskaya, O. G., Ryasny, V. G. & Saavedra, O. 1993 *Nuovo Cimento* A **106**, 257–263.

Sadoulet, B. 1991 *Nucl. Phys.* B (*Proc. Suppl.*) A **28**, 3–16.

Schutt, T. *et al.* 1992 *Phys. Rev. Lett.* **69**, 3425–3427; 3531–3534.

Seckel, D., Steigman, G. & Walker, T. P. 1991 *Nucl. Phys.* B **366**, 233–251.

Smith, P. F. 1986*a* In *Proc. 2nd ESO-CERN Symp.* (*Garching*), pp. 237–263.

Smith, P. F. 1986*b* *Z. Phys.* C **31**, 265–275.

Smith, P. F. 1991 *Ann. N.Y. Acad. Sci.* **647**, 425–435.

Smith, P. F. 1992 In *Proc. Conf. Trends in Astroparticle Physics*, pp. 311–325. Santa Monica: World Scientific.

Smith, P. F. & Lewin, J. D. 1990 *Phys. Rep.* **187**, 203–280.

Smith, P. F. & Lewin, J. D. 1992 In *Proc. Conf. Trends in Astroparticle Physics*, pp. 581–589. Santa Monica: World Scientific.

Spooner, N. J. C. *et al.* 1991 *Phys. Lett.* B **273**, 333–337.

Spooner, N. J. C. & Smith, P. F. 1993 *Phys. Lett.* B. (Submitted.)

Spooner, N. J. C., Smith, P. F. & Lewin, J. D. 1993 *Proc. XXIII ICRC.* **4**, 760–763.

Steigman, G. 1991 MPI (Heidelberg) preprint MPI-Ph/91-32.

Stodolsky, L. 1988 *Comments Nucl. Part. Phys.* **18**, 157–173.

Stodolsky, L. 1991 *Ann. N.Y. Acad. Sci.* **647**, 405–412.

Totsuka. Y. 1992 *Rep. Prog. Phys.*, pp. 477–430.

Young, B. A., Cabrera, B., Lee, A. T. & Dougherty, B. L. 1992 *Nucl. Instrum. Meth. Phys. Res.* A **311**, 195–216.