10.1098/rsta.2003.1294

THE ROYAL SOCIETY

Direct detection of weakly interacting massive particles using non-cryogenic techniques

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Published online 16 September 2003

A flux of weakly interacting neutral particles incident on the Earth would produce occasional nuclear-recoil events in any material. These could be detected as scintillation or ionization pulses in suitable target materials. Expected rates are in the range 1–10^{-4} events kg^{-1} d^{-1}. These must be distinguished from much higher rates due to backgrounds from gamma and beta background, even in deep underground locations. Methods of uniquely identifying nuclear recoils are described using crystal scintillators, scintillation and ionization processes in liquid xenon, and ionization tracks in gases. World progress on these techniques and future prospects are summarized. A possible future weakly interacting massive particle detector based on mechanical recoil of suspended microgranules is proposed which, with advances in nanotechnology, could eventually be extended to the detection of low-energy relic neutrinos.

Keywords: dark matter; WIMPs; particle detectors; underground physics; relic neutrinos

1. Experimental objectives and constraints

A number of experimental searches are in progress to detect weakly interacting particles in the mass range 10–1000 GeV, which could form a major fraction of the galactic dark matter. A particle candidate of particular interest is the hypothetical neutralino of supersymmetry theory (Ellis 2003; Roszkowski 2002), which is predicted to have a cross-section for interaction with nucleons in the range 10^{-5}–10^{-10} pb. Coherent interaction with atomic nuclei would result in observable nuclear recoils typically in the keV energy range, with event rates predicted to be in the range 1–10^{-4} events kg^{-1} d^{-1}.

Such energies and event rates are in principle observable using scintillation, ionization or low-temperature bolometric techniques, the major problem being to identify these events in the presence of the much higher background from ambient gammas, betas and neutrons produced by nearby radioactivity or by cosmic rays. This identification can be achieved either by a combination of signals (e.g. bolometric + ionization, scintillation + ionization) or by variations in signal pulse shape. Discriminating experiments of this type requiring millikelvin temperatures are described in

One contribution of 13 to a Discussion Meeting 'The search for dark matter and dark energy in the Universe'.

Kraus (2003). Non-cryogenic experiments (i.e. those above 100 K) based mainly on scintillation and ionization processes are discussed in this paper.

Although such detectors can discriminate between nuclear recoils and electron recoils from gamma/beta background, nuclear recoils identical to those which would be produced by dark-matter collisions can be produced by neutrons. A major source of neutron background is from cosmic-ray muons, which produce fast neutrons from any nuclei; it is this which necessitates the operation of experiments in underground locations, typically at a depth of 1000 m, to reduce the penetrating muon flux by a factor of about 10^6. A second source of neutrons arises from the interactions of alphas emitted by U or Th in the underground rock, or in the detector components. This must be removed by a combination of neutron shielding, pure materials and neutron-veto techniques.

In addition to a continuous low rate of nuclear-recoil events, two further signals, which can in principle demonstrate the galactic origin of the signal, may be sought in these experiments. The first of these is a seasonal modulation in the event rate, arising from the Earth's motion around the Sun as the Sun moves through the Galaxy, giving an annual variation of the speed (and hence flux) of dark-matter particles relative to the detector. For a non-rotating dark-matter halo, this effect would provide a 4% modulation in rate, with a maximum in June, and a 6% modulation in the product (rate × energy). This could be observed by long-term operation of sufficiently stable detectors of the type described in §§ 2 and 3 below. The second effect is directionality of the recoils, also arising from the Earth's motion through the dark matter, and giving a typical factor 2 forward/backward asymmetry in the direction of galactic motion. This would provide a large diurnal modulation of the recoils in any particular direction. The development of detectors with directional capability is discussed in § 4 below. In § 5 the possibility is discussed of a directional detector based on mechanical recoil of levitated microgranules, which might ultimately be extended to the detection of relic neutrinos.

2. Nuclear-recoil discrimination by pulse shape

The first limits on dark-matter event rates were set by the background rates in existing underground experiments using Ge ionization detectors. These detectors could not specifically identify nuclear-recoil events within the background, and the first detectors to make a significant improvement in nuclear-recoil limits were based on pulse-shape discrimination in scintillating NaI crystals, observed by pairs of low-background photomultipliers in low-background enclosures (Bernabei *et al.* 1999; Smith 1996). The mean emission time of the scintillation photons from nuclear recoils is about 0.75 of that for electron recoils from either gamma background or beta-decay events (Smith *et al.* 1999). This difference is sufficient to detect statistically a small population of nuclear-recoil events in the presence of a much larger distribution of gamma/beta background events (figure 1) or to set a 90% confidence limit on such a signal. In this way, using crystals 5–10 kg in mass, signal limits were lowered to below 10 events $kg^{-1}\ d^{-1}$, equivalent to a weakly interacting massive particle (WIMP)-nucleon scattering cross-section of less than 10^{-5} pb.

Following this, the Rome (DArk MAtter (DAMA)) group, operating at the Gran Sasso laboratory, scaled up their detector to 10 crystals totalling 100 kg. After a few years of operation, they reported an apparent seasonal modulation of their total

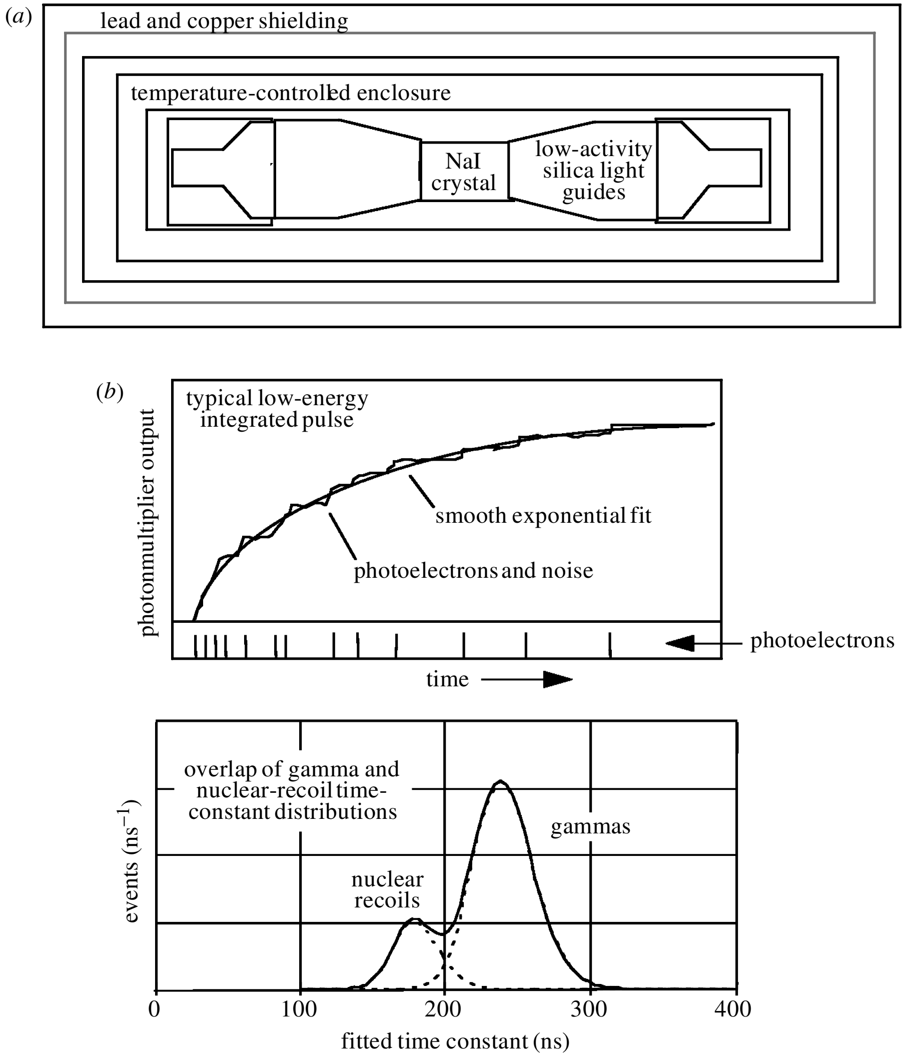

Figure 1. (*a*) Typical low-background detector based on scintillation in sodium iodide. (*b*) Typical distribution of pulse rise times showing separation of nuclear-recoil and electron-recoil populations.

count rate (Bernabei 2000*a*,*b*), with a mid-year maximum as expected for a dark-matter signal modulation (figure 2). It was not possible to identify this specifically as a nuclear-recoil signal within the larger background, so it could in principle be a modulation in the gamma, beta or alpha background, or an unidentified systematic. The effect was confined to low energies of less than 10 keV, whereas a fluctuation in other backgrounds might be expected to be present also at higher energies. If interpreted as a dark-matter signal, the modulation would correspond to a particle of mass 40–80 GeV and interaction cross-section (with a single nucleon) in the range 2×10^{-6}–2×10^{-5} pb.

The other major NaI programme, developed in parallel by the UKDMC at the UK Boulby Mine, encountered difficulties in attempting to confirm or refute this result,

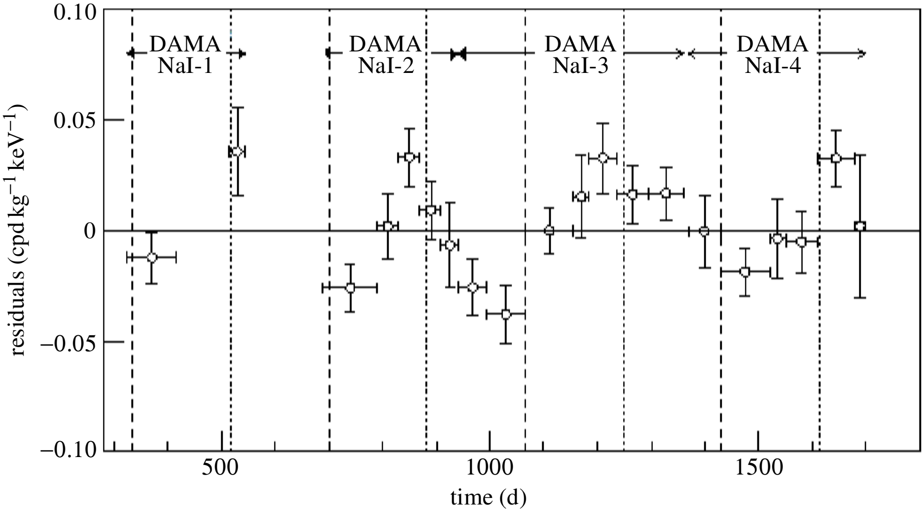

Figure 2. Seasonal modulation of total count rate in the DAMA 100 kg NaI detector, after subtraction of the constant average rate (from Bernabei 2000*a*,*b*).

owing to the presence of unidentified systematics in the time-constant distribution, possibly due to alphas emitted from the crystal surface layer. This emphasized the need for the DAMA group to identify its effect as modulation of a nuclear-recoil signal rather than a modulation of background—for example, by partitioning the event pulses into sets with above- or below-average time constant.

However, other types of experiment have recently progressed to sensitivity levels below that of the Rome NaI array, without observing any signal in the 'DAMA region'. The UK collaboration, although successful in removing the systematics in NaI crystals, switched to the more sensitive experiment ZEPLIN I (ZonEd Proportional scintillation in LIquid Noble gases) using liquid xenon as target. This is based on the fact that scintillation pulse shape differences in liquid xenon are 2–3 times larger than those in NaI, giving a correspondingly greater separation of a nuclear-recoil signal (Davies *et al.* 1994). The ZEPLIN I detector consists of a hemispherical target volume containing 3 kg of liquid xenon, from which scintillation light can be observed simultaneously by three photomultipliers. This assembly is surrounded by a 30 cm thick liquid scintillator, serving as both an active Compton veto and passive neutron shield, and finally by 20 cm thick lead gamma shielding (figure 3). Light pulses from the xenon are digitized and the mean photoelectron arrival time t_{m} is determined for each pulse, the values of t_{m} forming a smooth distribution for the gamma/beta background. Generation of a population of nuclear recoils with a neutron source shows that these produce a distinctive distortion of the tail of the t_{m} distribution (figure 4). After several running periods totalling 90 d, no nuclear-recoil population was detected, and from the statistical (90% confidence) limit on such a signal a new limit on the interaction cross-section for massive particles can be derived as a function of the hypothetical particle mass.

The limits from several world experiments at the time of writing (February 2003) are shown in figure 5, together with the signal region corresponding to the DAMA annual modulation effect. The IGEX curve is a total count rate limit from the 6 kg Ge

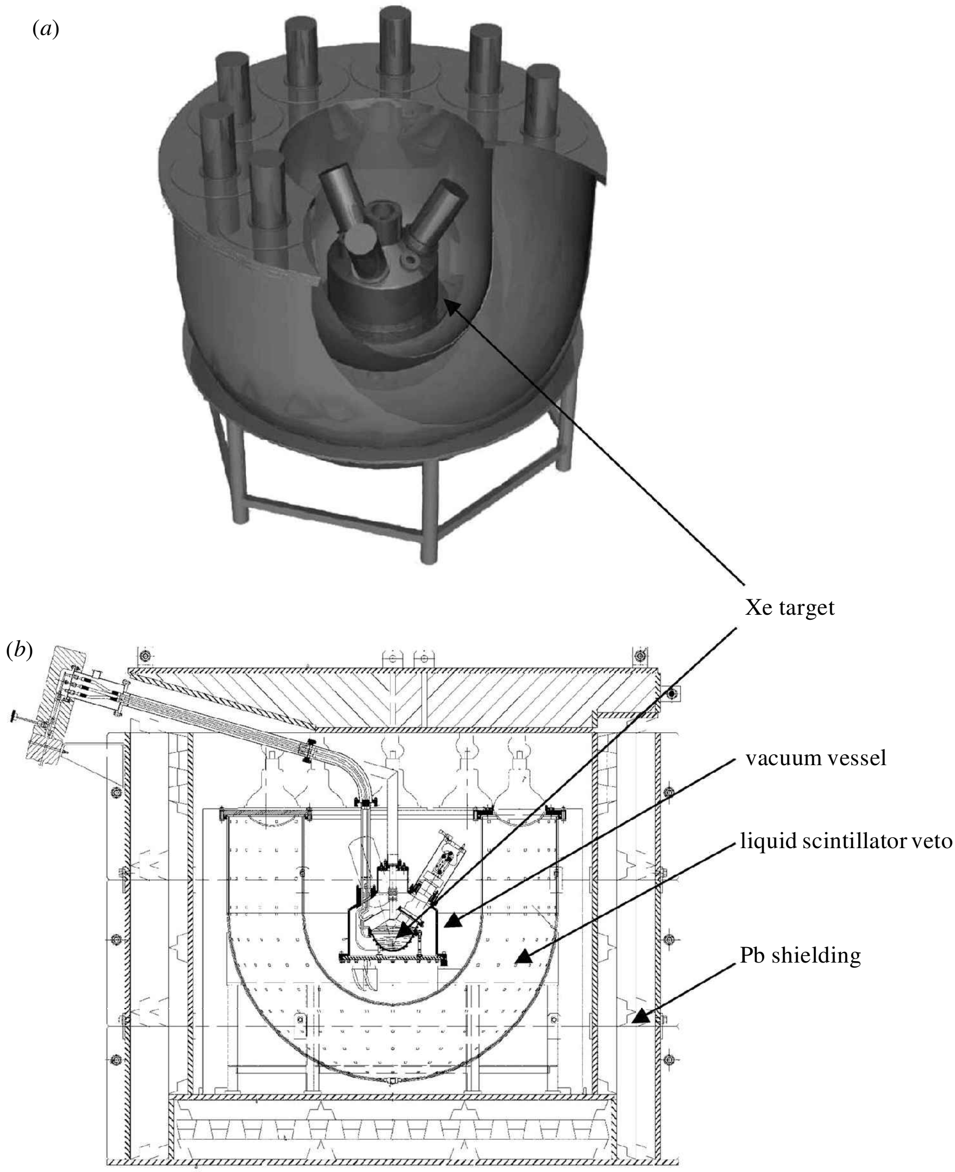

Figure 3. (*a*) ZEPLIN I liquid xenon vessel viewed by three photomultipliers; (*b*) ZEPLIN I assembled within liquid scintillator veto and lead shielding.

detector in the Canfranc underground laboratory (Morales *et al.* 2000), which does not specifically identify nuclear recoils but nevertheless achieves a sufficiently low background rate to overlap part of the DAMA region. The EDELWIESS (Benoit *et al.* 2001) and CDMS (Brink *et al.* 2003) curves are Ge ionization/bolometer experiments discussed in the accompanying low-temperature review (Kraus 2003), and which in combination exclude most of the DAMA region. The recent new limit curve from ZEPLIN I (Smith 2003; UKDMC 2003) lies well below the entire DAMA region,

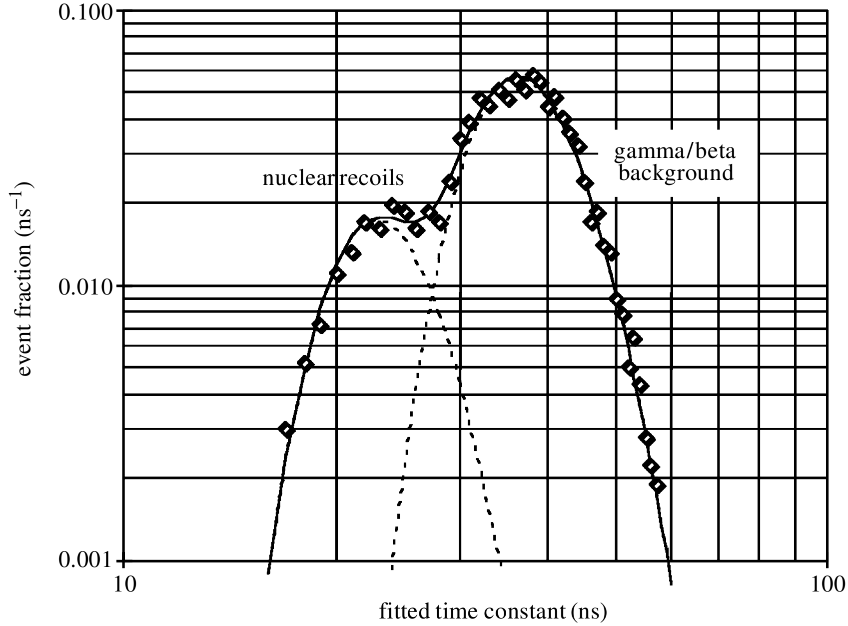

Figure 4. Response of ZEPLIN I to a mixture of neutron and gamma fluxes, showing separated populations of nuclear recoils produced by neutron–nucleus collisions.

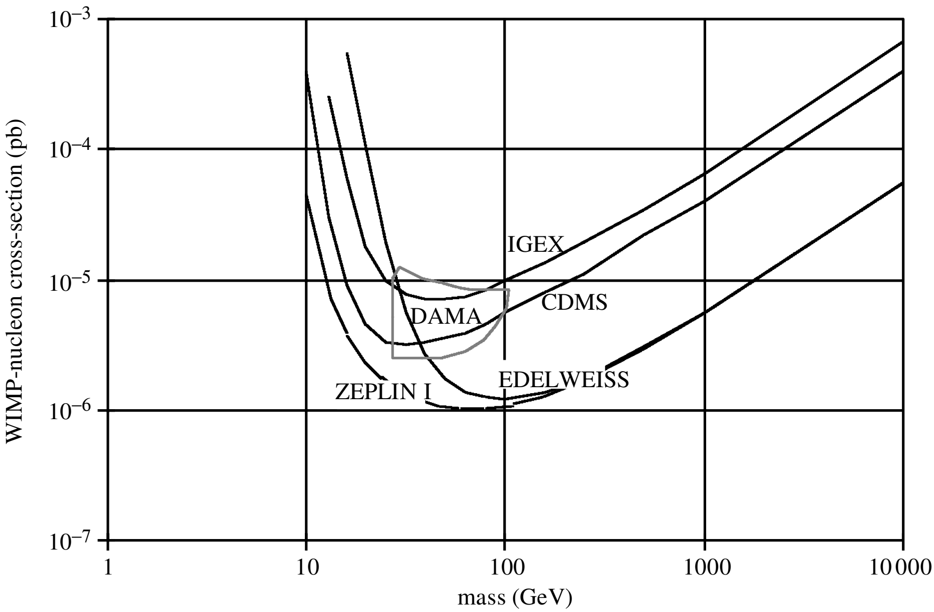

Figure 5. 90% confidence limits on cross-section for WIMP-nucleon scattering versus WIMP mass for several world experiments (referenced in text). The closed contour shows the apparent signal region from the DAMA annual modulation effect, based on the same galactic halo parameters.

which is thus now excluded with 99% confidence by several experiments using different target elements.†

Attention has therefore returned to the objective of achieving further substantial improvements in sensitivity to reach the levels 10^{-7}–10^{-10} pb, which is the theoretically favoured region for the neutralino cross-section. Plans are in hand for improvements and scale-up for both cryogenic and non-cryogenic experiments. In the case of the latter, a further factor of 10 is in principle achievable by extended running of ZEPLIN I, and another factor of 10 could be achieved simply by scaling up or replicating ZEPLIN I to a target mass greater than 100 kg. However, faster progress can be achieved by a more advanced liquid-xenon technique which uses both scintillation and ionization signals to give a more complete separation between signal and background. Current progress on this is described in the next section.

3. Nuclear-recoil discrimination by two-phase liquid-xenon detectors

Liquid xenon can be made to produce two scintillation signals from a given event. The first of these is the primary scintillation pulse, as used in ZEPLIN I; the second is created by drifting and accelerating the local ionization from the event to create a secondary scintillation pulse. Laboratory studies have shown an order of magnitude difference between the ratio of primary to secondary pulses for nuclear recoils and background gamma events (Benetti *et al*. 1993). This initial scheme was subsequently replaced by the concept of obtaining the two pulses from a two-phase configuration. The principle is shown in figure 6*a*. The primary scintillation pulse S1 occurs in the liquid at the location of the event, as before. An electric field is then used to drift the ionization from the event to the liquid surface and extract it into the gas phase. A stronger electric field then creates an avalanche, producing an amplified secondary scintillation pulse S2. Test chamber results using neutron and gamma sources (Cline *et al*. 2000) show that events plotted in terms of S1 and S2 form two distinct populations corresponding to nuclear-recoil events and gamma events (figure 6*b*). This will apply above some threshold energy, which is dependent on the efficiency of light collection from the primary scintillation.

Two detectors based on this principle are the ZEPLIN II and III projects, planned as successors to ZEPLIN I at the Boulby Mine. ZEPLIN II is being built as a collaboration between US and UK groups (Cline *et al.* 2003; Smith 2002) using the design shown in figure 7. The target mass is 30 kg, with a depth of 12 cm, through which ionization is extracted vertically into the gas phase, with both primary and secondary scintillation pulses observed by an array of photomultipliers located in the gas. The parallel project ZEPLIN III, under construction as a collaboration between European and UK groups (Sumner 2001), incorporates some alternative design options, with a view to obtaining the lowest possible energy threshold. An array of photomultipliers is located in the liquid xenon close to and underneath the 7 kg disc-shaped target region for maximum light collection (figure 8), and a higher electric field applied over the 3–5 cm depth is used to maximize extraction of ionization from low-energy

† The exception to this conclusion would be an abnormally large spin-dependent interaction on the odd proton in the Na nucleus, for which there appears to be no theoretical justification or likelihood. It should also be noted that, although the DAMA contour can be expanded downwards by using a broader range of assumptions about the galactic halo (Bernabei 2002), these extended assumptions also reduce the other experimental limits by similar factors, so that they remain below the DAMA region.

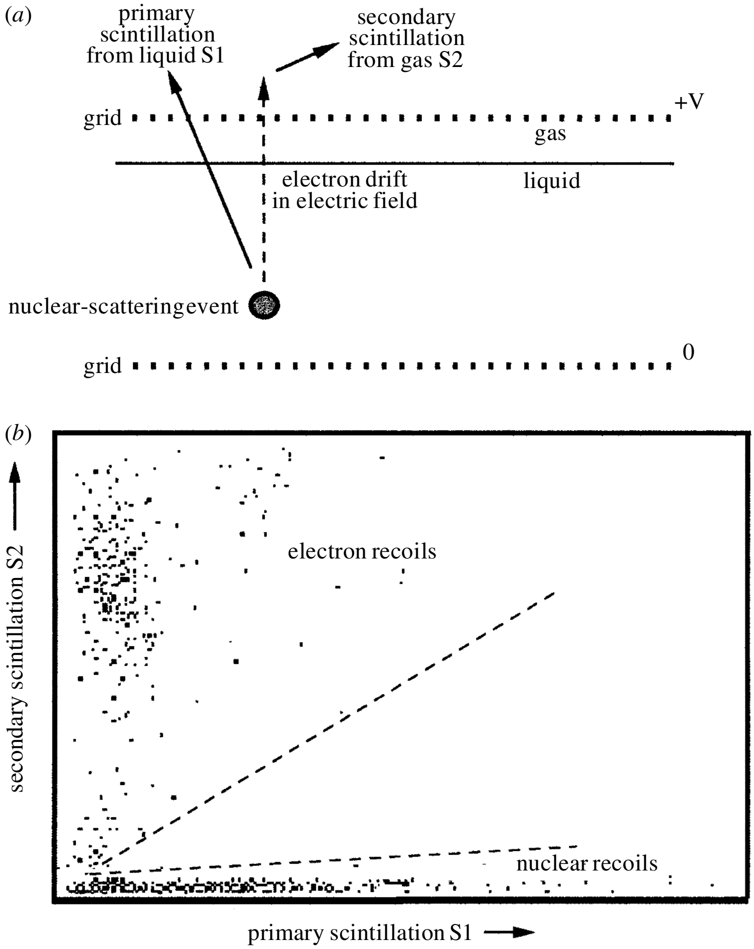

Figure 6. (*a*) Production of primary and secondary from interactions in liquid xenon. (*b*) Separation of events into populations of nuclear recoil and electron recoil events on S1–S2 plot (from Bernabei 2000*a*,*b*).

events. Both of these detectors are funded and under construction. Both should yield at least a one-order-of-magnitude gain in sensitivity within two years.

In addition to extending the dark-matter search to lower sensitivity levels, a second purpose of these two projects is to establish design and performance indicators for a much larger project. On the assumption of eventual neutralino detection at cross-sections of 10^{-9}–10^{-10} pb, the need for reasonable event rates to study will necessitate a target mass greater than 1 ton, probably subdivided into 4–10 separate modules. Because of the high cost of such a system, it is essential for the design principles to be proven on smaller prototypes. The performance of ZEPLINs I, II and III will thus provide the basis of the design of the much larger system. Work on two-phase detectors has also recently been reported by the Columbia group (Aprile 2002) and by Japanese groups (Moriyama 2003; Suzuki 2003).

Figure 9 summarizes past and projected future progress on the assumption that world funding can be sustained for continued improvement and scale-up of these

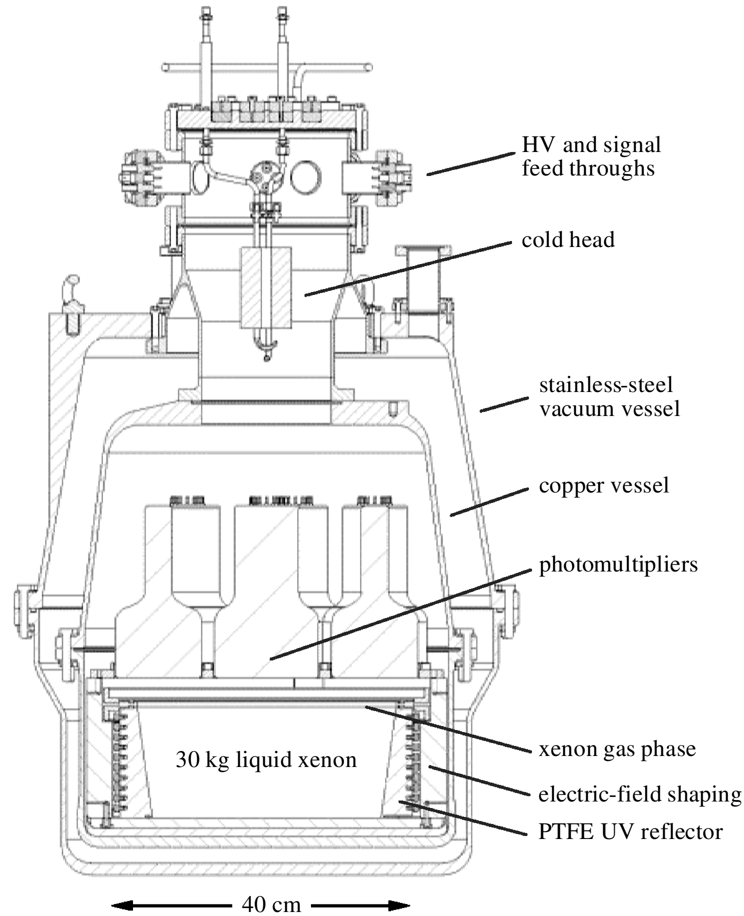

Figure 7. Cross-section view of ZEPLIN II, based on the two-phase principle, using a 30 kg liquid-xenon target viewed by seven photomultipliers.

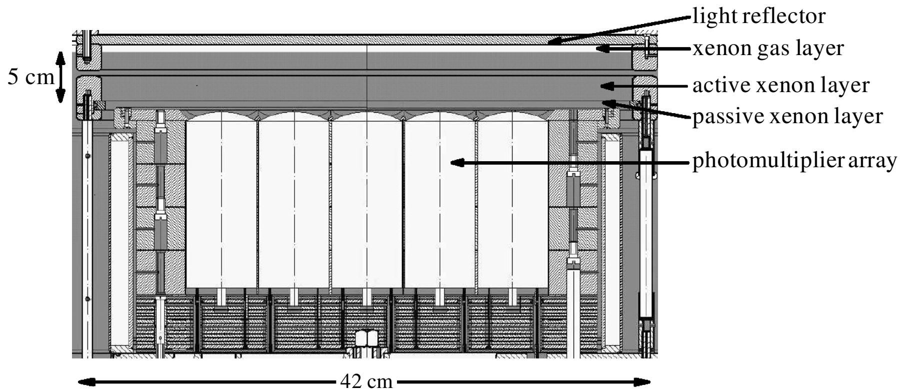

Figure 8. Target region of ZEPLIN III, showing a shallow 7 kg liquid-xenon target viewed by an array of immersed photomultipliers for high-efficiency collection of scintillation light.

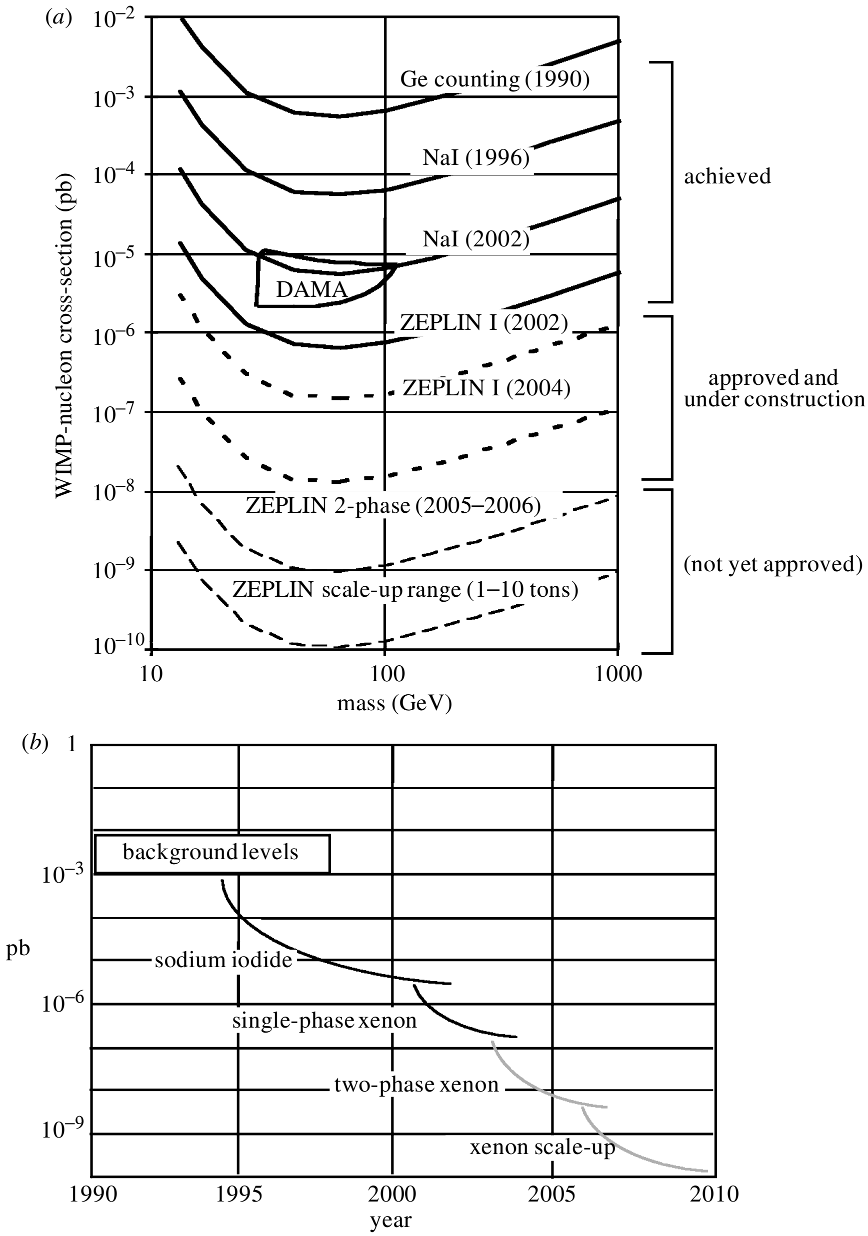

Figure 9. (a) Projected sensitivity improvements using non-cryogenic detectors: achieved limits from existing detectors (solid curves); detectors approved and under construction (thick-dashed curves); detectors not yet funded (thin-dashed curves). (b) Improvements in cross-section sensitivity with time by progressive detector development and scale-up to larger target mass.

detectors. In figure 9a, the solid curves show the succession of achieved dark-matter limits using pulse shape discrimination in NaI and Xe. The thick-dashed curves show the estimated further gains from the currently approved programme of two-phase liquid-xenon detectors. Finally, the thin-dashed curves show the likely sensitivity range for xenon detectors with a total target mass of 1–10 tons. Figure 9*b* summarizes the progress in sensitivity versus time, illustrating that each new technique produces an initial rapid gain, followed by a slower rate of improvement until the next technological advance or scale-up in target mass can be brought into operation. If this progression can be achieved, one can thus expect to reach the lowest predicted neutralino levels during the period 2005–2010, by which time the large particle accelerator Large Hadron Collider (LHC) will also be in operation and capable of searching for the production of the predicted heavy neutralino particle in high-energy collisions.

4. Directional gaseous detectors

As mentioned in § 1, seasonal modulation and directionality potentially provide two methods of ultimately demonstrating a correlation between a nuclear-recoil signal and galactic motion. It is important to search for these effects specifically on a separated recoil signal because of the ambiguities inherent in attempting to infer or extract them from a total population dominated by background events. Even then, a problem with the seasonal modulation is that it requires a year of stable data to observe the effect, followed by several more annual cycles to confirm it. In contrast, the directional asymmetry is converted automatically to a diurnal modulation by the Earth's rotation.

The difficulty of observing directionality of nuclear recoils in solid or liquid targets is that the nuclear-recoil range is only of the order of 1×10^{-6}–3×10^{-6} cm (dependent on the nuclear charge and mass) at a typical recoil energy of 10–20 keV, thus producing essentially isotropic scintillation and ionization effects. Some studies have been made of range discrimination using a suspension of submicrometre crystal grains in a liquid scintillator (Tovey *et al.* 1997), and this might in principle be extended to directionality using anisotropic grains. The use of the intrinsically anisotropic organic scintillators stilbene and anthracene has also been discussed (Belli *et al.* 1992; Shimizu *et al.* 2003; Spooner *et al.* 1997) but their relatively poor light output and 'quenching factor' (reduced light output for nuclear recoils relative to electron recoils from gamma interactions) probably preclude the development of these as competitive dark-matter detectors.

The use of low-pressure gaseous targets is more promising. These can provide observable recoil ranges, of the order of a few millimetres for pressures in the region of 0.01 atm. The much lower target density, compared with a solid or liquid target would require a correspondingly larger total volume, perhaps 100–1000 m^3, to provide the same target mass. However, this is by no means excessive compared with detectors of similar or larger volume already in operation for neutrino detection (using liquid-scintillator or water targets).

An initial key difficulty was that the tracks had to be drifted, by an electric field, through the volume to an end plane for amplification and read-out but without significant diffusion, which would distort or completely disrupt the track. In the first laboratory-scale tests of this scheme, this was achieved by applying a longitudinal magnetic field to inhibit the radial motion of the electrons (Buckland *et al.* 1994). For large gaseous dark-matter detectors this would require correspondingly large volumes of magnetic field, which appears unrealistic and prohibitively expensive for an underground experiment. This problem was overcome by the idea of 'negative-ion

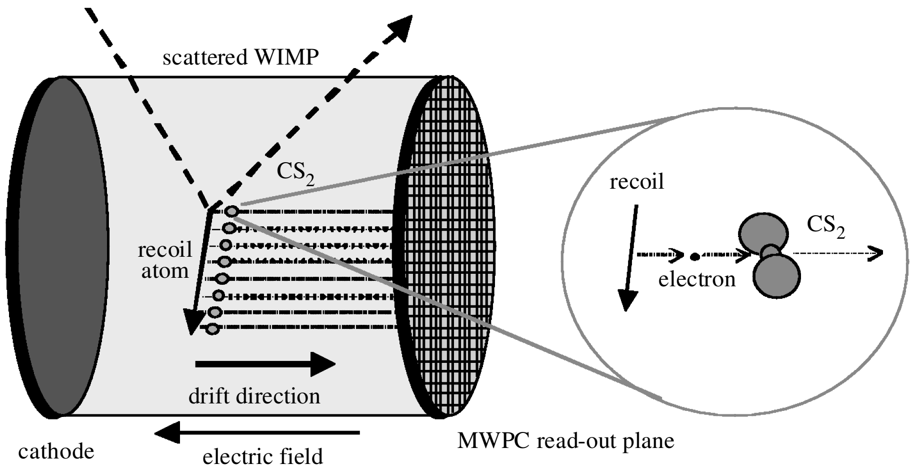

Figure 10. The principle of gaseous directional detectors, based on the attachment of ionization electrons to CS_2 molecules to minimize track diffusion (Martoff *et al.* 2000).

drift' (Martoff *et al.* 2000), in which the electrons forming the track attach themselves to electronegative molecules to form heavy negative ions, which can then be drifted without serious diffusion (figure 10). The proposal was to use CS_2 molecules as the electronegative component, which would themselves be suitable as dark-matter target material, or alternatively to mix them with another target gas such as xenon. Results from small test chambers showed this principle to work as predicted, and to be sufficiently stable and reliable for scale-up to larger volumes (Martoff *et al.* 2000; Snowden-Ifft *et al.* 2000).

Operational detectors of this type, with the generic acronym DRIFT, are being developed in a collaboration between UK and US groups for installation initially in the Boulby Mine. DRIFT I is a $1\,m^3$ prototype containing $160\,g$ CS_2 gas and currently undergoing underground performance tests (figure 11). It is of interest that there is a choice of two modes of operation for DRIFT:

(i) the ultimate mode in which sufficiently low pressure is used to obtain measurable recoil tracks, as discussed above, or

(ii) a dark-matter search mode operating with a higher pressure to obtain a larger target mass, and using ionization density to distinguish gamma background from nuclear recoils.

It is also necessary to distinguish the latter from alphas produced by U and Th impurities in the detector vessel and detector wires. As with the solid and liquid detectors, background neutrons (from remaining cosmic-ray muons or U/Th activity in nearby materials) can produce nuclear recoils and must therefore be rejected by shielding or veto techniques.

It seems likely that DRIFT detectors will initially be operated in the higher pressure search mode, and in the event of a signal would then be scaled-up to investigate directionality at lower pressure. This would also be the case in the event of a signal observed in a non-directional detector such as ZEPLIN, which would then provide the incentive to assemble gaseous detector modules $1000\,m^3$ in volume.

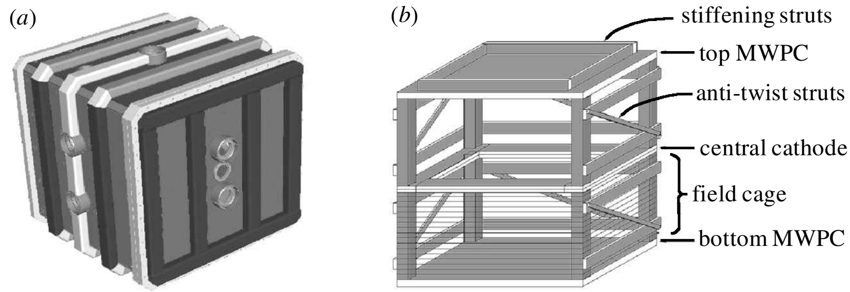

Figure 11. DRIFT I gaseous detector prototype. (*a*) A 1 m^3 stainless-steel vacuum vessel. (*b*) Internal structure, showing field cage, central cathode and multi-wire proportional counter (MWPC) read-out. (Schematic provided by DRIFT collaboration: UKDMC, Temple University, Philadelphia, PA, Occidental Coll, Lawrence Livermore National Laboratory.)

A further merit in pursuing the two approaches lies in the ability to verify that a signal arises from a coherent weak interaction. Due to the A^2 dependence of the latter there would be, firstly, in a CS_2 target a dominance (95%) of S recoils over C recoils, compared with approximately equal numbers of S and C recoils from the neutron background. Secondly, there would be a factor of 20 times more events per kilogram in a xenon target (average $A^2 \approx 1.7 \times 10^4$) than in a CS_2 target (average $A^2 \approx 800$) since the basic WIMP–nucleon interaction would be the same for each. In practice, this difference would be further modified by the different (energy-dependent) nuclear form factors. It would thus be a remarkable confirmation of the origin of the signal to observe different event rates in the two targets which, after removing the form factor and coherence corrections, reduce to the same basic dark-matter interaction.

5. Suspended microgranule detector

Another possibility for directional WIMP detection, which would be more compact than a gaseous detector, arises from previous work by the author on coherent relic-neutrino detection. Although the relic-neutrino background cannot be detected by conventional single-particle interactions (because the interaction cross-section and energy transfer is too small for these ultra-low energy neutrinos) coherent interaction with bulk matter could result in a detectable mechanical force (Smith & Lewin 1983, 1984, 1987). One method of observing this would be to set up a levitated array of small granules (less than 10^{-5} cm diameter) with which individual neutrino interactions would result in a very small mechanical recoil (Smith 1990). Such a detector may become possible in the future with foreseeable advances in nanotechnology.

Application of this principle to WIMP detection may be possible much sooner because of the much higher momenta associated with 100 GeV particles gravitationally bound to the Galaxy (Smith 2003). For typical galactic velocities *ca.* 1×10^7–3×10^7 cm s^{-1}, collisions with a 1 μm diameter Si granule would result in optically detectable recoil velocities *ca.* 100–1000 μm s^{-1} (figure 12*a*). In contrast to the neutrino case, there is no bulk coherence (i.e. coherence extending over atomic distances) in the case of WIMPs. Their larger momenta gives coherence only over nuclear dimensions, as in the other WIMP detectors discussed above. This means that the total mass of the granule array (figure 12*b*) would need to be similar to the target mass of

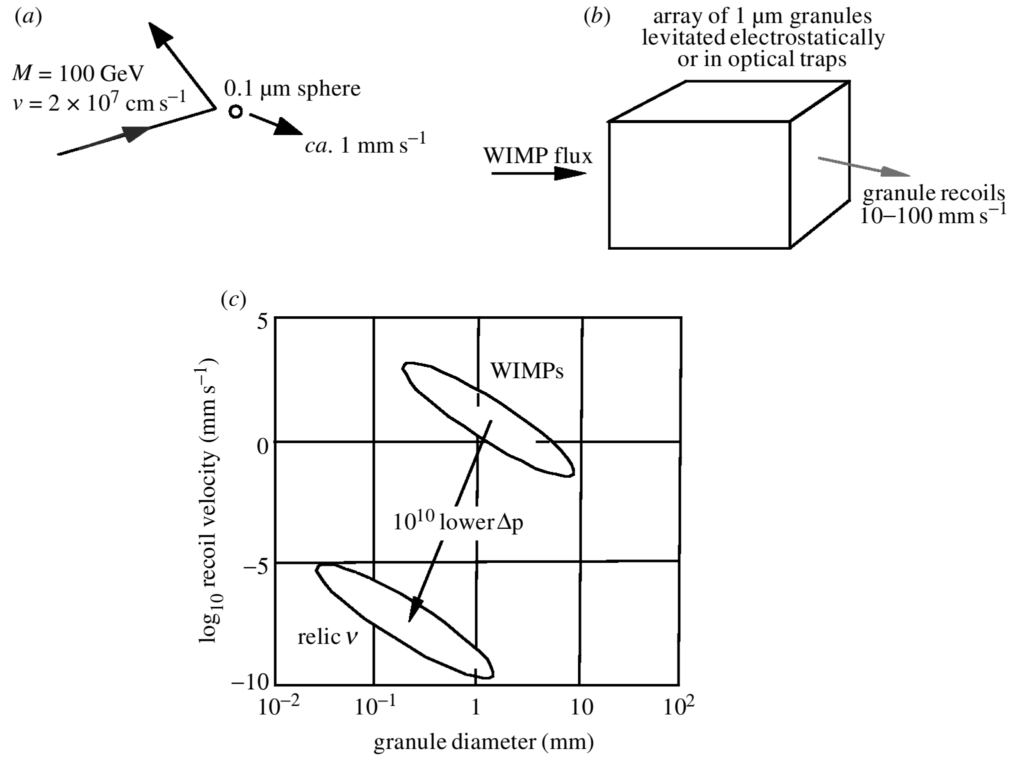

Figure 12. Proposed 'mechanical' detection with levitated granule arrays. (*a*) Typical WIMP–granule collision; (*b*) detector based on levitated granule array as target; (*c*) typical parameter range for WIMP or relic-neutrino detection.

a conventional detector, but could in principle provide directionality in a more compact system than a low-pressure gas. The reason for optimism that such a detector could be developed arises from recent rapid progress in extending the 'optical tweezers' principle (for applications in chemistry and biology) to the creation of larger arrays (both two dimensional and three dimensional) of micrometer-sized granules, held in optical traps formed by computer-generated optical holograms (Dholakia *et al.* 2002; Garces-Chavez *et al.* 2002). Moreover, such arrays can be designed to be self-assembling, suggesting that indefinite scale-up may be possible.

For particle detection, shielding and background problems will be similar to those of conventional detectors, and soluble by similar shielding and veto techniques. It is therefore suggested that development work on these 'mechanical' granule detectors, together with appropriate optical-read-out techniques, could begin immediately, with a view to directional WIMP detection within a few years. With the experience gained, the principle could be progressively extended to the nanoparticle scale needed for eventual relic-neutrino detection. Figure 12*c* compares the granule sizes and recoil-velocity measurements needed in the two cases, showing that the technological gap between the two objectives is about a factor 10^{10} in momentum transfer sensitivity. This suggests that a further development period of at least 30–40 years may be needed to achieve detection of relic neutrinos. However, past predictions have often underestimated future progress. At the time of proposing the neutrino hypothesis in

1930, Wolfgang Pauli believed that such a particle could never be detected, whereas with subsequent development of reactors and accelerators neutrinos were not only detected but subsequently used routinely as nuclear probes. Another remarkable underestimate of future progress was that by the science fiction novelist Jules Verne, who in the nineteenth century foresaw the possibility of video picture transmission (Verne 1889), but as the outcome of a millennium of technological development!

The author acknowledges support from an individual emeritus research grant by the Leverhulme Trust. Prepublication results for ZEPLIN I are shown by permission of UKDMC.

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UKDMC 2003 (Submitted.)

Verne, J. 1889 *In the 29th century.*