Experimental Limits on Particle Dark-Matter Candidates [and Discussion]

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Experimental limits on particle dark-matter candidates

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The experimental limits on some of the particle candidates for the dark matter are discussed. The main part of the paper is about neutrinos, which are the only particles known to exist that are possible candidates, and the present evidence about neutrino mass is reviewed. This is followed by a discussion of the limits on two candidates that have provoked considerable experimental interest: the magnetic monopole, and the supersymmetric particle, the photino. The paper concludes with a brief account of a recently developed calorimetric detector and of its possible use in detecting dark-matter candidates, such as the photino.

INTRODUCTION

The dark matter or 'missing mass' problem is still unresolved. Its existence has been well established for many parts of the Universe from studies of the motion of stars within galaxies and of galaxies within clusters. These studies have indicated that in these regions the mass of dark matter is an order of magnitude greater than that of visible material. If this were generally true it would mean that the density of matter in the Universe is close to the critical density, which is the state predicted by inflationary models.

There have been many suggestions as to what this material might be, including faint stars, planets, and rocks, as well as exotic candidates such as neutrinos, magnetic monopoles, photinos, axions and black holes. Many cosmological arguments (see, for example, Sciama 1984; Blumenthal *et al.* 1984) have been made for favouring certain of these suggestions, but in this paper only the experimental limits on some of the particle candidates will be discussed.

NEUTRINOS

It has been speculated for some time that massive neutrinos may provide the dark matter in galactic halos and the critical density. If only one kind of neutrino provided the critical density, then a simple cosmological argument (see, for example, Sciama 1984) gives the mass of this neutrino in the range $25\ \text{eV} \leqslant m_\nu \leqslant 100\ \text{eV}$. Hence the excitement in 1980 when Lubimov *et al.* (1980) announced evidence for the electron antineutrino having a mass of $m_\nu \approx 30\ \text{eV}$. This led to a considerable amount of experimental activity and the present status of these experiments will now be discussed.

The electron neutrino

(i) *Tritium end point experiments*

Lubimov *et al.* (1980) used the traditional way of extracting information on the mass of the electron neutrino, which is measuring the shape near the end point of the electron energy spectrum in tritium β-decay. The sharing of energy between the electron and the neutrino gives rise to a shape given by:

$$N(E) \propto |M_{if}|^2 F(Z,E)\ pE(W_0-E)\,[(W_0-E)^2 - m_\nu^2 c^4]^{\frac{1}{2}},$$

where $N(E)$ is the number of electrons lying within the energy interval E to $E+\mathrm{d}E$, p is the electron momentum, W_0 is the total decay energy, m_ν is the mass of the neutrino, $F(Z,E)$ is the Fermi function, which corrects for the Coulomb interaction between the electron and the nucleus, and M_{if} is the matrix element for the β-decay. For $m_\nu = 0$ the expression reduces to:

$$N(E) \propto |M_{if}|^2 F(Z,E)\ pE(W_0-E)^2.$$

Hence, if $\mathrm{K} \equiv [N/pEF]^{\frac{1}{2}}$ is plotted against E (a Kurie plot), a straight line results for $m_\nu = 0$ in an allowed β-decay where the matrix element has no momentum dependence. This is the case for tritium β-decay assuming the interaction is pure (V–A). Kurie plots for tritium β-decay for finite and zero neutrino mass are shown in figure 1. It can be seen that the effect of finite neutrino mass is most noticeable near the end point.

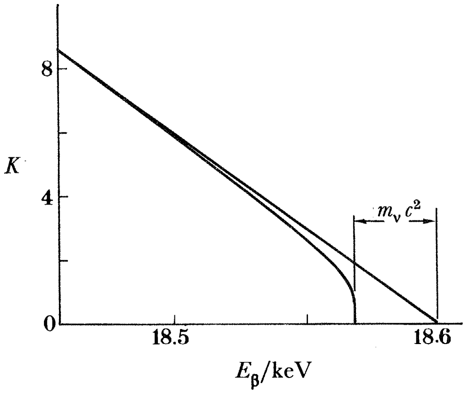

FIGURE 1. Theoretical Kurie plots for tritium β-decay with $m_\nu = 0$ and $m_\nu = 30$ eV.

Further experimental work has been carried out by the Moscow group since 1980 and the latest results are shown in figure 2 (Boris *et al.* 1985). The Kurie plots are for three different sources. There appears to be very good evidence for $m_\nu \neq 0$ and the best fit value is for $m_\nu = 35$ eV with their 90% confidence limits given by 20 eV $\leqslant m_\nu \leqslant$ 45 eV. These values do depend on the final state spectrum assumed in the decay of the tritium atoms in the valine source. However, their non-zero value for m_ν is not caused by an error in the calculated final state spectrum used, as their model independent limit, obtained by assuming that there are no excited final states, is $m_\nu > 9$ eV (90% confidence limit). These results, though, have provoked a number of comments, in particular over the effect of resolution on the analysis.

The Kurie plots in figure 2 are curved near the end point, unlike the theoretical curves of figure 1. This is, in part, due to the effect of the finite experimental resolution (ca. 20 eV) and, as stressed by Simpson (1984*a*) and Bergkvist (1985*a*, *b*) it is crucial in the analysis of the data that this experimental resolution is very well measured. This can be seen qualitatively by considering the case when the actual mass of the neutrino is zero. Finite resolution will change the shape of the observed Kurie plot to one like the solid line shown in figure 3*a* and *b*. If the resolution has been measured correctly then the Kurie plot upon correction will be like the

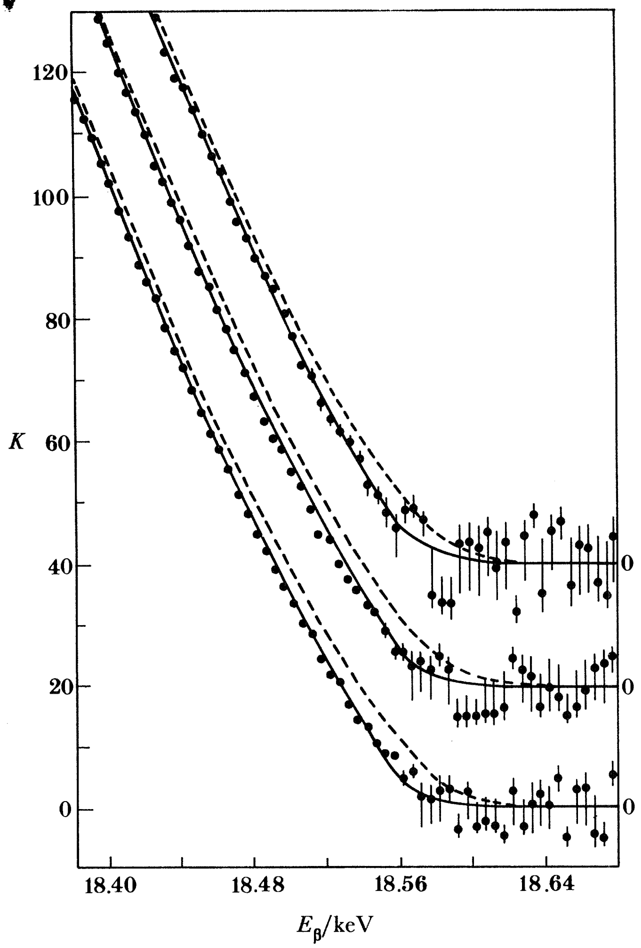

FIGURE 2. Experimental Kurie plots for tritium β-decay (Boris 1985) for three sources. The lines are the overall fit to the data for which $m_\nu = 35$ eV. The dashed lines are the theoretical spectrum with $m_\nu = 0$ and W_0 from the overall fit.

dashed line in figure 3*a*, i.e. indicating $m_\nu = 0$. However, if the resolution is taken to be larger than it actually is then upon correction the Kurie plot will look like the dashed line in figure 3*b*, i.e. indicating $m_\nu > 0$. It is thus vital to measure the resolution correctly otherwise artificial neutrino masses may result. The Moscow result is the subject of some controversy in this respect (Bergkvist 1985*b*) and there are several groups throughout the world who are presently trying to check this result by a variety of techniques.

At Oxford, a method under investigation is to use a cylindrical mirror analyser as the spectrometer with a tritiated Langmuir–Blodgett film as the source (see figure 4). The advantage here is a source a few monolayers thick and hence of very accurately known thickness and composition, which is useful in determining accurately the experimental resolution. The basic design of the instrument is shown in figure 5 (Jelley 1985). The source, is deposited on the surface of a cylinder mounted inside an angle defining holder. Electrons from different heights on the source cylinder are brought to the same focus by using the technique (Bergkvist 1964, 1971, 1972) of having a potential gradient down the source equal to the energy dispersion of the spectrometer. Those electrons emerging from the source at an

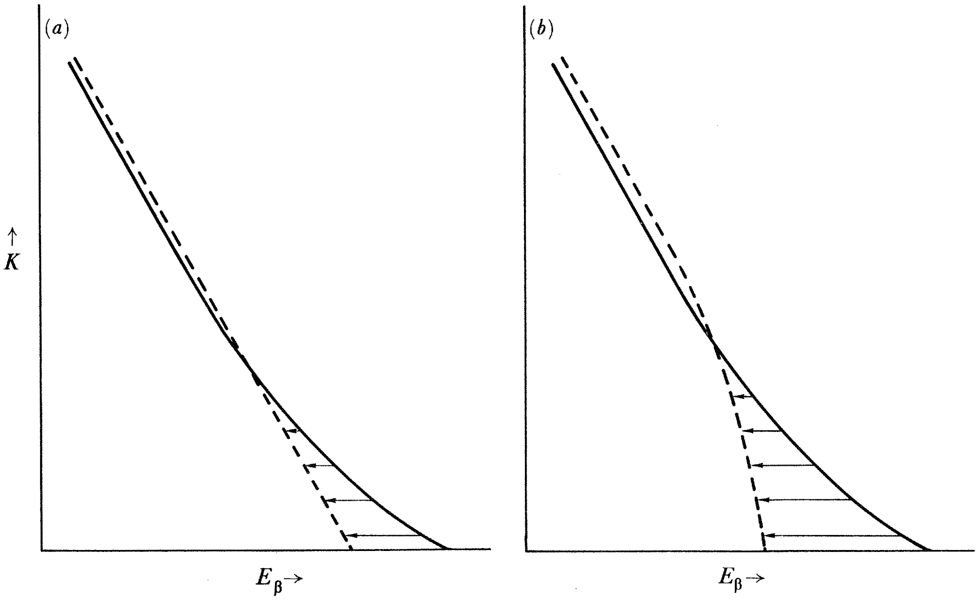

FIGURE 3. The solid lines in (*a*) and (*b*) shows qualitatively the effect of resolution on the Kurie plot with $m_\nu = 0$. The dashed line in (*a*) represents the Kurie plot for $m_\nu = 0$ with correction for resolution and in (*b*) represents the Kurie plot for $m_\nu = 0$ with over correction for resolution.

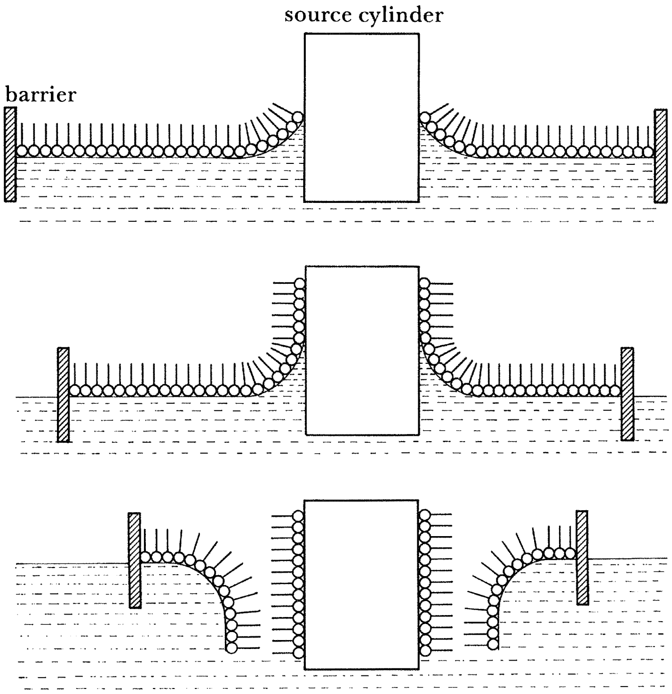

FIGURE 4. Illustration of the Langmuir–Blodgett technique of transferring a monomolecular layer on an aqueous subphase to a cylindrical substrate. The circle represents the hydrophilic end of the molecule and the line the hydrophobic tail. The barrier maintains a constant surface pressure.

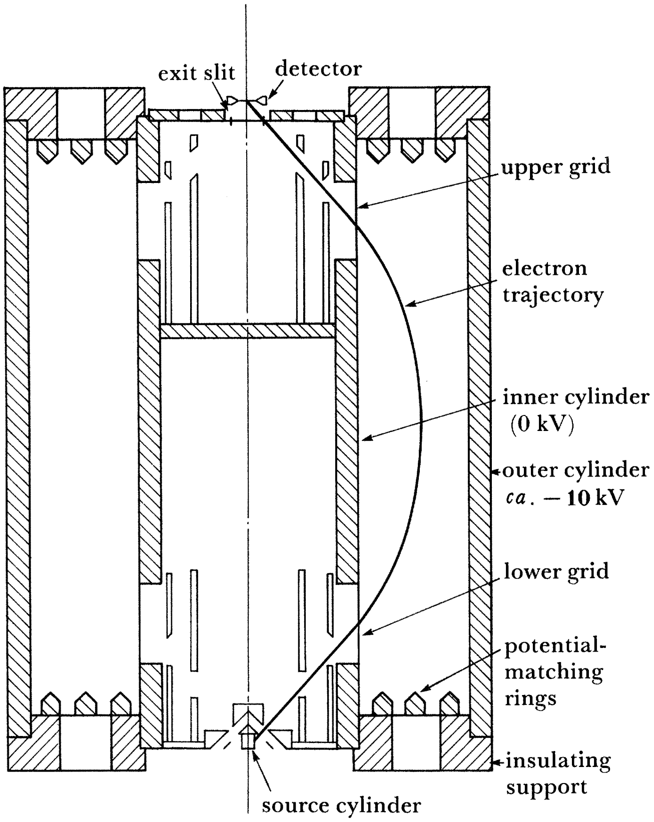

Figure 5. Schematic diagram of the Oxford cylindrical mirror analyser.

angle *ca.* 45° to the vertical pass through a grid made solely of vertical wires. They are then deflected by a $1/r$ field until they reach the upper grid, after which the electrons then travel to a second-order focus just below the detector where they are counted. By scanning the source voltage from, say, −4 kV to −5 kV relative to the inner cylinder, the β spectrum of the electrons near the end point can be measured. This and several of the other experiments underway (Simpson 1984*b* and references therein; Robertson 1985 and references therein) are nearing completion and results are likely to be available within a year.

The Moscow result also stimulated ideas of alternative ways of measuring the electron-neutrino mass via electron capture (Bennett 1981; De Rújula 1981). The interesting suggestion made by De Rújula was to look at the process of internal bremsstrahlung in electron capture (IBEC).

(ii) *IBEC experiments*

In IBEC an electron is captured and the energy released is shared between a neutrino and a photon: $e^- + p \rightarrow n + \nu + \gamma$. In an analogous way to ordinary beta-decay the shape of the photon spectrum near the end point is sensitive to the mass of the neutrino. Normally IBEC is a very weak process compared with ordinary electron capture and the photon rate is too low for a useful measurement. De Rújula pointed out, however, that there could be resonant enhancement of the photon yield close to the end point, and if the Q-value of the decay were favourable there is the possibility of a very good measurement of the neutrino mass.

Since his suggestion there has been considerable experimental effort and a limit of

$m_\nu < 500$ eV has been obtained from studying IBEC in the decay of ^{193}Pt (Jonson *et al.* 1983). The Q-value for this decay is 56.3 keV, which is rather high. The decay of ^{163}Ho has a Q-value of *ca.* 2.3 keV, which is more favourable, and has been closely studied (Yasumi *et al.* 1983). However, it appears that experimental difficulties may well limit the accuracy of this method and make it uncompetitive compared with the traditional method based on beta-decay.

(iii) *Double beta-decay*

Double beta-decay is made possible through the pairing contribution to the binding energy of nuclei. The process can proceed either with the emission of two neutrinos or with no neutrinos emitted. The latter process can only take place if the neutrino is a Majorana particle, for then particle and antiparticle are identical and it is possible for the emitted neutrino to be absorbed. If, however, both the weak interaction is pure (V–A) and the neutrino has zero mass, then this process can not proceed as the helicities of the emitted and absorbed neutrino are exactly opposite. Any limit on the occurrence of neutrinoless double β-decay can therefore be used to calculate an upper limit on the mass of a Majorana neutrino.

A very sensitive experiment has recently been carried out to look for the neutrinoless double β-decay of ^{76}Ge (Bellotti *et al.* 1984). In this experiment the germanium was in the form of a germanium semiconductor detector. The signature of the decay is the emission of just two electrons that share the decay energy. If both stop within the detector then a peak corresponding to 2.041 MeV will be seen. The experiment took place in the Mt Blanc tunnel in a very low background environment and the limit placed on the neutrinoless mode was calculated as equivalent to a limit of less than 4 eV mass for a Majorana neutrino.

Recently, the accuracy with which mass limits can be calculated from the absence of neutrinoless double β-decay has been questioned (Caldwell 1984 and references therein). However, a result of $m_\nu < 4$ eV is not necessarily in conflict with a mass of 35 eV deduced from a beta-decay experiment. This is because the neutrino could be a Dirac particle (like an electron) or a mixture of Majorana neutrinos of different mass which can have a very different effective mass in double beta-decay than in ordinary β-decay (Wolfenstein 1981; Doi *et al.* 1983).

The number of neutrino flavours

The electron neutrino is not the only type of neutrino and it is important to know how many different flavours there are, as they could all contribute to the dark matter. Cosmological calculations of nucleosynthesis and estimates of the primordial He abundance have indicated that the number of neutrino flavours is less than four (Barrow & Morgan 1983). Recently a comparable limit on the number of neutrinos has been able to be set from data on the production of W and Z particles at the CERN $p\bar{p}$ collider (Di Lella 1986).

The method used was to measure the ratio of the production cross sections of the W and Z particles and from this infer the decay width of the Z particle, which is dependent on the number of neutrino flavours, N, with mass less than the Z particle through the decay mode $Z \rightarrow \nu\bar{\nu}$. A direct method would have larger systematic uncertainties as the width Γ_z is comparable with the experimental resolution. The result of $1.7 \text{ GeV} < \Gamma_z < 2.9 \text{ GeV}$ (90% confidence limit) was compared with the theoretical expression for the width, and the limit $N < 5.4$ (with ± 1.0 theoretical uncertainty) was deduced. This means that the number of additional neutrino flavours to those already known is now severely restricted by both cosmological and particle physics arguments. At present there are only three flavours known, the electron, the muon and the tau neutrinos.

The muon and tau neutrinos

As in beta-decay, the masses of the ν_μ and ν_τ have been inferred from measurements of the energy spectra of charged particles produced in conjunction with the neutrino. Abela *et al.* (1984) have studied the decay $\pi \rightarrow \mu\nu$ at rest and from measurement of p_μ have found the limit $m_{\nu_\mu} < 250$ eV (90% CL). For the tau neutrino a limit of $m_{\nu_\tau} < 70$ MeV (95% CL) has been deduced from studying the decay $\tau^+ \rightarrow \pi^+\pi^-\pi^+\nu_\tau$ produced in the reaction $e^+e^- \rightarrow \tau^+\tau^-$ (Argus collaboration 1985). Combining these limits with those from the cosmological argument (Lee & Weinberg 1977) that stable neutrinos in the mass range *ca.* 100 eV to *ca.* 2 GeV would lead to a density in the Universe greater than the critical density, suggests that m_{ν_μ} and m_{ν_τ} are both less than *ca.* 100 eV. To obtain such a limit directly will be very difficult indeed. However, the phenomenon of neutrino mixing, if it occurred, could yield this information on the masses of different neutrino flavours.

Neutrino mixing

Neutrino mixing occurs when the neutrino flavours are not mass eigenstates but a mixture of different mass eigenstates. The idea that an eigenstate of the weak interaction is not a mass eigenstate is not an unprecedented one in particle physics. In particular, the production and decay of the K mesons is a well-known example where the weak interaction eigenstate is a 50:50 mixture of K^0 and $\overline{K^0}$. Another example is in hadronic weak decays where the eigenstate involves a mixture of different quarks expressed in terms of the Cabbibo angle. If neutrino mixing occurs then both distortion in beta-spectra and neutrino oscillations may be seen.

(i) *Distortion in beta-decay spectra*

In January of 1985 J. J. Simpson (1985) reported a kink in the electron spectrum from tritium β-decay at an energy of 1.5 keV, which is 17 keV below the end point (see figure 6). He interpreted this as evidence for a 17 keV heavy neutrino and, more precisely, as indicating that what was emitted in β-decay was a mixture of a light (mass < 50 eV) and a heavy (17 keV) neutrino, with the probability of the heavy neutrino being 3%. This would give rise to a kink at 1.5 keV because above this energy only the light neutrino can be emitted whereas below both neutrinos can be emitted resulting in an increase in the decay rate.

Simpson's result led to some interesting theoretical speculations and conclusions (Dugan *et al.* 1985; Glashow *et al.* 1985) as well as a number of experiments aimed at checking his interpretation. If the weak interaction eigenstate is a mixture of a light and a heavy neutrino then a kink will be seen in all beta-decay spectra 17 keV below the end-point. Previous work, which generally had not studied spectra as close as 17 keV from the end point, could not rule out the existence of such kinks. However, recently Altzitzoglou *et al.* (1985) and Datar *et al.* (1985) have looked at ^{35}S beta decay and have found no evidence for such a kink, so the kink in the tritium spectrum is not due to the emission of a heavy neutrino.

The tritium spectrum was obtained by implanting tritium in a silicon semiconductor detector and it is possible that the kink is a consequence of some neglected interaction of the

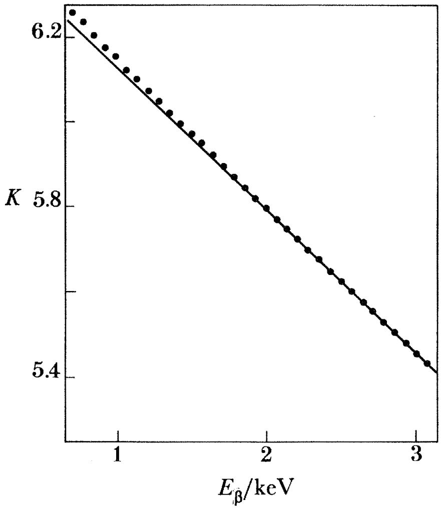

Figure 6. Low-energy part of the Kurie plot of tritium β-decay (Simpson 1985) obtained with a silicon semiconductor detector in which tritium was implanted.

emitted electron with the silicon. Also in the analysis of the tritium data several approximations are used in evaluating the distortion of the electron spectrum arising from the Coulomb interaction between the helium nucleus, the orbital electron and the emitted electron. Haxton (1985) has pointed out that these approximations will be suspect when the de Broglie wavelength of the electron is comparable with the Bohr radius of the helium atom. This occurs at an electron energy of *ca.* 1 keV, which is where the kink is observed, and Haxton (1985) has concluded that it is plausible that a careful treatment of atomic effects will provide a conventional explanation of the observed tritium β-decay spectrum.

The absence of any observed kink in the β-ray spectra has only ruled out the possibility of the electron neutrino being a mixture of different mass neutrinos for a certain range of mass and mixing values. At the 90% confidence limit the range $5\ \text{keV} < m_{\text{heavy}} < 460\ \text{keV}$ with a mixing probability of greater than 1% has been eliminated (Datar *et al.* 1985; Schreckenbach *et al.* 1983), but there is a wide range of lower mass difference values not excluded. These may be accessible experimentally through the study of neutrino oscillations.

(ii) *Neutrino oscillations*

If the neutrino flavours are a mixture of different neutrino mass eigenstates then neutrino oscillations are expected. Consider, for example, that the electron and tau neutrino produced in a weak interaction are two orthogonal mixtures of a light and a heavy neutrino:

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta, \quad \nu_\tau = -\nu_1 \sin\theta + \nu_2 \cos\theta.$$

As the time dependences of the phases of ν_1 and ν_2 are different and are given by $e^{(iE_{\nu 1}t/\hbar)}$ and $e^{(iE_{\nu_2}t/\hbar)}$, respectively, then an electron neutrino will become a tau neutrino and vice versa. It is worth pointing out that this phenomenon of neutrino oscillations requires not only that at least two of the neutrino mass eigenvalues are different but that mixing also occurs.

Many searches for oscillations have been made and these can be divided into two types:

occurrence experiments, where the signature of a different neutrino appearing in a beam of neutrinos is searched for, and disappearance experiments, where the flux of neutrinos is measured at two distances and a decrease is looked for. In the simplest case of two mass eigenstates mixing, the probability of a new type of neutrino occurring is given by

$$P(\nu_e \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2(1.27\,L\Delta^2/E),$$

where L is the distance in metres after the production of the ν_e beam, Δ^2 is the mass squared difference in electronvolts squared and E is the neutrino energy in megaelectronvolts. The probability is greatest when $\Delta^2 \sim E/L$. Experiments on accelerators and on reactors, for example, therefore probe different regions of Δ^2.

The latest situation is that there is no experimental evidence for any neutrino oscillations but, as mentioned above, this does not mean that neutrinos have no mass. The result from the Le Bugey (Cavaignac *et al.* 1984) reactor which had suggested a $\Delta^2 = 0.2\ \mathrm{eV}^2$ and $\sin^2 2\theta = 0.25$ now appears to be in conflict with more recent results from the Goesgen reactor (Gabathuler *et al.* 1984, 1986). An interesting speculation, which is still a possibility, is that the solar neutrino problem is the result of neutrino oscillations with $\Delta^2 > 10^{-11}\ \mathrm{eV}^2$ and $\sin^2 2\theta \sim 1$, although the uncertainty in the flux of solar neutrinos does not allow any definite conclusion to be drawn (Lubimov 1984).

There thus appears to be no evidence for a finite neutrino mass other than the Moscow result which is itself still the subject of controversy. Moreover, cosmological arguments (Hut & White 1984; Blumenthal *et al.* 1984; Frenk, this symposium) suggest that the neutrinos are not a significant part of the dark matter as it would then be difficult to understand galaxy formation. Several other particle dark matter candidates have been discussed, for example axions (see discussion by Smith after this paper) and quark nuggets (Ellis, this symposium), but many of these are very difficult to investigate experimentally. However, two which have attracted considerable experimental interest recently are the magnetic monopole and the photino.

The magnetic monopole

In 1982 Cabrera (1982) announced that he had seen an induced current in a superconducting loop which was consistent with the passage of a magnetic monopole through the loop. As a monopole passes through a loop there is a change in flux which induces a current whose magnitude depends on the loop's self-inductance (see figure 7). Since then there has been considerable experimental activity but no clear signal of a monopole has been seen (Carrigan 1985).

On astrophysical grounds the absence of observed monopoles is felt to be not too surprising. The monopole is predicted to be extremely heavy (some 10^{16} times the mass of a proton) and if there were sufficient monopoles around for them to make up the dark matter then it has been argued that the galactic magnetic fields would have long since died away. The argument, however, does not require a complete absence of monopoles but puts an upper limit, called the Parker bound (Parker 1970), on their number. At present the experimental limit on the number of monopoles is some three orders of magnitude higher than this upper bound (Carrigan 1985).

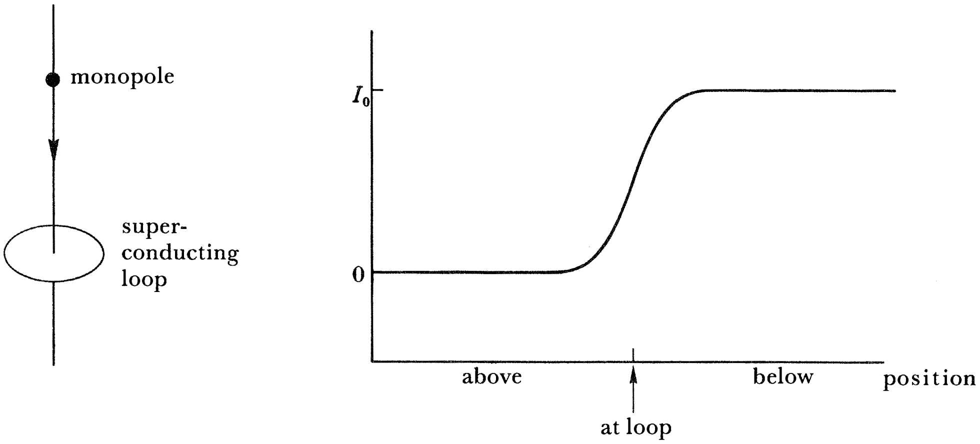

FIGURE 7. Illustration of the effect of a magnetic monopole passing through a superconducting loop. The induced current I_0 is given by $I_0 = h/eL$, where L is the self-inductance of the loop.

THE PHOTINO

Another particle which is, at present, a favoured candidate for dark matter is the photino. This is the supersymmetric partner to the photon and has spin $\frac{1}{2}$ and no charge and is predicted to have a mass of the order of several GeV. Such particles could be produced in the laboratory in a high-energy electron–positron collision and a possible process $e^+e^- \rightarrow \gamma\tilde{\gamma}\tilde{\gamma}$ is shown in diagrammatic form in figure 8.

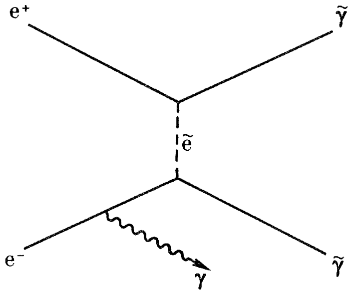

FIGURE 8. Feynman diagram for the process $e^+e^- \rightarrow \gamma\tilde{\gamma}\tilde{\gamma}$.

It is characteristic of such processes that two supersymmetric particles are involved, in this case the selectron and the photino. The probability or cross section for such a process depends on the masses of both the selectron and the photino so limits on the rate of such a process give coupled limits on the selectron and the photino mass. The energy in the collision is shared among the final particles. The photinos escape detection, as they have no charge and are very weakly interacting, and a single photon is looked for. The coupled limits for this process deduced in a recent experiment are shown in figure 9 (ASP collaboration 1986). If the selectron mass were 30 GeV, for example, then the photino would have to have a mass greater than 10 GeV but if the selectron mass is greater than *ca.* 50 GeV then this experiment does not provide a limit on the photino mass.

At present there is no limit on the mass of the photino and there is no evidence at all for any of these hypothetical particle candidates. If they should exist, however, it might be possible to detect them by using a calorimetric detector.

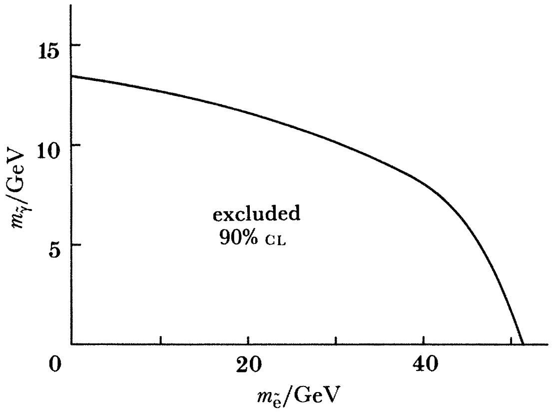

FIGURE 9. Coupled limits on the mass of the selectron and photino obtained by the ASP collaboration.

CALORIMETRIC DARK-MATTER DETECTORS

The use of calorimeters is well established in nuclear physics. In 1927 C. D. Ellis & A. Wooster measured the energy release in the β-decay of ^{210}Bi by calorimetry and found that it was significantly less than the maximum electron energy, which was one of the reasons which led Pauli to postulate the existence of the neutrino.

A recent experimental innovation is the development of very low temperature, high sensitivity calorimeters (see, for example, Coron *et al.* 1985; Booth *et al.* 1984). In one of these (Coron *et al.* 1985) an absorber is held at a very low temperature where its specific heat capacity

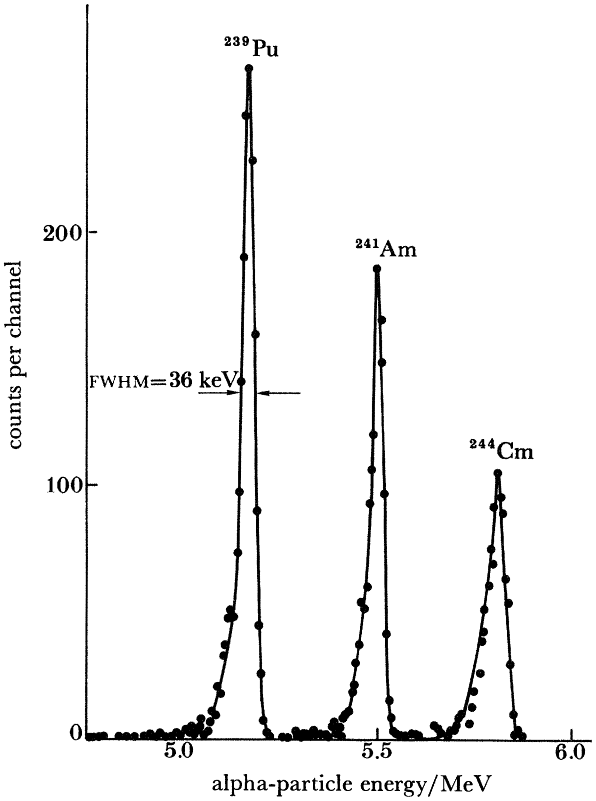

FIGURE 10. α-particle spectrum from a composite α-source obtained with a small diamond absorber at 1.3 K coupled to a germanium thermistor (Coron *et al.* 1985).

is very small so a small deposition of energy by the incident radiation can give a significant temperature rise. This small rise in temperature is detected by a very sensitive thermometer and the result of detecting α-particles from a composite α-source is shown in figure 10. The resolution is better than 1 part in 100 and it is hoped with improved electronics that a resolution of better than 1 part in 1000 will be achieved.

Such new detectors would open up a number of interesting possibilities. Their high resolution could be useful in trying to measure the electron neutrino mass and it might also enable a more stringent limit to be placed on neutrinoless double β-decay. In particular, as detection of radiation does not rely on ionization, as semiconductor detectors do, but just on the heat produced, they might be able to detect possible dark-matter candidates such as the photino, provided the background can be made small enough.

Conclusion

The electron antineutrino is the only particle candidate for dark matter with a non-zero mass claimed for it and the results of experiments aimed at verifying this claim are eagerly awaited. There is at present no confirmed evidence for any of the more exotic particle candidates for the dark matter but experimental detection of them, should they exist, may soon be a possibility.

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Discussion

P. F. Smith (*Rutherford Appleton Laboratory, Chilton, Oxfordshire*). I wish to summarize the possibilities for direct detection of neutral elementary particles that could constitute the galactic dark matter. The candidates fall into three classes: (1) neutrinos, with mass 10–30 eV; (2) any light boson, for example the hypothetical axion, with mass typically 10^{-5}–10^{-1} eV and (3) any new heavy particle, for example the photino, with mass perhaps in the range 1–10^3 GeV.

Neutrinos could, in principle, be detected via coherent scattering from bulk matter giving a very small force on a massive target 'tuned' to the typical galactic neutrino wavelength *ca.* 60 μm (Smith & Lewin 1983, 1984, 1985). However, the exceptional level of mechanical, thermal and electrical isolation needed would imply a very low-temperature zero-gravity experiment requiring typically an orbiting system of volume 40 m^3 and temperature less than 50 mK. This is clearly not possible in the foreseeable future, and no valid terrestrial alternative has so far been devised.

The other two (and now more favoured) classes of particle do, however, offer very good prospects for feasible experiments in the near future. Light bosons could be detected by conversion to photons in a magnetic field or in magnetized material (figure D1) whereas heavy particles could be detected by interaction with nuclei and the subsequent conversion of the nuclear recoil energy to phonons, the latter being detectable at low temperatures, either directly or after thermalization, as a temperature rise (figure D2).

Conversion of axions to photons via the two-photon coupling in vacuum has been discussed by Sikivie (1984, 1985*a*, *b*), with refinements by Krauss *et al.* (1985*b*), indicating a possible

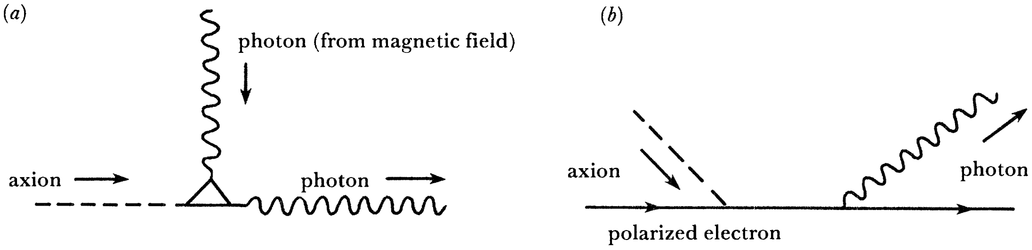

Figure D 1. Axion to photon conversion processes: (*a*) conversion in vacuum via two-photon coupling, one photon being supplied by a static magnetic field; (*b*) conversion via coupling to electron spin and subsequent emission of 'Compton' photon.

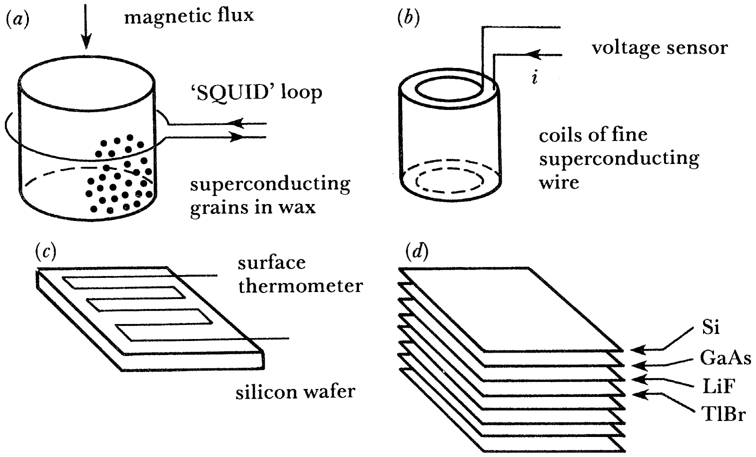

FIGURE D 2. Examples of calorimetric nuclear recoil detectors: (*a*) superheated superconducting grains in magnetic field, producing magnetic flux pulses; (*b*) superconducting wires or filaments carrying near-critical current, producing voltage pulses; (*c*) crystalline slab, producing temperature pulses; (*d*) mixed-material version of (*c*), consisting of stack of slabs with varying nuclear mass and spin.

experiment in which axions are converted to microwave or infrared photons in a large volume of magnetic field. Because of the wide range in the possible axion frequency (*ca.* 1–10^4 GHz) and the extremely narrow bandwidth (*ca.* 10^3 Hz) arising from the low kinetic energy, the signal would be very difficult to find, requiring a careful and lengthy scan over the available frequency range. A specific resonant-cavity experiment covering the range 1–10^2 GHz has been discussed by Morris (1984), who estimates a scanning time of three months for each factor-two frequency range.

Another way of converting to photons is to use Compton-like scattering from polarized electrons. This is in principle more efficient (because it is first order in the electromagnetic coupling, α, whereas the vacuum process is proportional to α^2), and should thus involve smaller detector volumes. The original suggestion of Krauss *et al.* (1985*a*) based on conversion in polarized ferrite has subsequently encountered the difficulty that the Lagrangian based on free electrons would not apply to an insulator (Krauss *et al.* 1985*b*), but it is still possible that some modified scheme based on very thin magnetized conducting plates or filaments might be feasible (note that polarized material would not be necessary for the case of scalar bosons).

An alternative approach would be to detect the flux of light bosons from the interior of the Sun (produced by the inverse of the preceding process). The detection processes are similar, except that the energy is now defined by the photon spectrum of the *ca.* 10^7 K solar core, so that solar axions would convert to X-rays in the 1 keV region. Thus an experiment based on conversion in a large volume of magnetic field might be feasible if the X-ray background can be reduced sufficiently, but the potentially more efficient detection process based on scattering from electrons encounters at the present time both unresolved practical problems (arising from the range of less than 1 μm of the X-rays in the detector material) and unresolved theoretical questions regarding the correct treatment of the process in solid matter. It is of interest to note that, because the conversion to X-rays is peaked in the forward direction, such experiments could be made highly directional and would clearly demonstrate the solar origin of any observed signal. The galactic axion detectors could also be designed with some degree of directionality, giving a small but significant difference in signal when oriented parallel or perpendicular to the galactic orbit.

Whereas further theoretical study is required for these light boson detectors, more immediate plans are possible for heavy particle detectors based on calorimetric principles. In these, the incoming particle scatters elastically from a nucleus, the recoil energy converting to phonons and producing a significant temperature rise if the energy is contained within a sufficiently small volume of material. For many high-purity crystalline materials, and also for superconductors, the electronic contribution to the specific heat is negligible and the T^3 dependence of the lattice specific heat enables very high energy sensitivity to be achieved at low temperatures, in particular below 0.1 K. As a specific example, a particle of mass 10 GeV and velocity $10^{-3}\,c$ incident upon a 0.5 mm silicon cube at 60 mK would, for the average 2 keV nuclear recoil energy, produce a 20 mK temperature rise. This level of sensitivity, combined with the commercial availability of dilution refrigerators now capable of cooling quite large volumes (e.g. 10 litres) down to 5–10 mK, makes it possible to consider the development of a prototype 1–10 kg detector for heavy galactic particles. Typical event rates, estimated by Goodman & Witten (1985), might be 1 $\text{kg}^{-1}\,\text{d}^{-1}$ for photinos of mass 10–10^2 GeV, or 10^2–10^3 $\text{kg}^{-1}\,\text{d}^{-1}$ for scalar neutrinos of mass 1–10^3 GeV.

Such calorimetric or ‘bolometric’ particle detectors have been under consideration or development, for other purposes, for a number of years (see, for example, Fiorini & Niinikoski 1983; McCammon *et al.* 1984; Coron *et al.* 1985). Several versions of the idea have been studied for solar and supernova neutrinos, in particular the use of flux changes in superheated superconducting grains (Drukier & Stodolsky 1984), voltage pulses in fine superconducting filaments (Smith 1986*a*) and silicon blocks with surface thermometers (Cabrera *et al.* 1985). Drukier (1985) has also considered the application of the superconducting grain idea to heavy supersymmetric particles.

A particularly interesting possibility, which we are now studying in detail, is to make use of the variety of pure crystalline materials developed for the semiconductor and optics industries. These have the attraction firstly that they are available in the form of thin flat discs or wafers, on which can be deposited or implanted a temperature sensing layer, and secondly that the available variation in nuclear mass and spin would provide important additional information regarding the identity of the signal. Thus, for incoming mass M_1 and nuclear mass M_2 the energy transfer is proportional to $4\,M_1\,M_2/(M_1+M_2)^2$, giving maximum signal when the nuclear mass and particle mass are equal. In addition, the photino would not interact at all with spinless nuclei. One can therefore envisage using, for example, alternating layers of the materials silicon (5% spin), LiF, GaAs, TlBr (all 100% spin), for which the different counting rates would provide a necessary condition to be satisfied by any genuine signal. With a sufficiently good energy resolution the recoil spectrum itself would provide further confirmation. Background counts due to single collisions from ordinary neutral particles (in particular neutrons) are likely to be a serious problem common to all proposed calorimetric detectors, and will necessitate both careful shielding design and the use of constructional materials low in natural radioactivity. These problems are currently under study.

Such a ‘first stage’ detector would not be sensitive to the direction of the incoming particles. However, further refinements of this technique can be envisaged, based on the direct detection of the phonons before thermalization and, if this can be achieved, it may also then be possible to devise a way of sensing the nuclear recoil direction. In general, low-temperature energy detectors represent an important direction for future detector development, with applications in many areas of astrophysics and particle physics, in addition to offering the prospect of the first attempts at direct detection of the dark matter.

For a more detailed review of this topic, see Smith (1986*b*).

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