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Particle Physicists' Candidates for Dark Matter

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Particle physicists' candidates for dark matter

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A review is presented of the candidates for dark matter that arise in different particle theories. These include massive neutrinos and monopoles in grand unified theories, axions arising from attempts to explain CP conservation in the strong interactions, stable supersymmetric particles such as photinos, gravitinos or sneutrinos, and other possible stable relics from the Big Bang. Wherever possible, relations to laboratory information and possible experiments directly sensitive to the different dark-matter candidates are discussed.

1. Introduction

It is the task of other authors in this symposium to discuss the indirect observational evidence for dark matter, and the benefits it may bring to theories of galaxy formation. My task is to review the different particle candidates for dark matter. They range in mass from quark nuggets, which may have mass 10^{55} GeV or more, through strange matter and electroweak nuggets, plancktons, which are stable particles with mass $O(10^{19})$ GeV, magnetic monopoles, which may have mass $O(10^{16})$ GeV, shadow matter, which might have almost any mass, stable supersymmetric particles with mass between $O(1)$ and $O(10^3)$ GeV, massive neutrinos with mass $O(1)$ GeV–$O(100)$ eV, axions with mass $O(10^{-12})$ GeV and finally polonyions with mass $O(10^{-15})$ GeV. Clearly, the collective mind of the particle physicists is fertile! In the rest of this paper, I will try to describe each dark-matter candidate, explain why it is postulated, and mention some key properties with possibilities for its experimental detection.

2. Quark nuggets and strange matter

These are some of the most conservative candidates, in that no completely new particle is postulated, only a new, denser form of conventional strongly interacting matter (Witten 1984). The idea is that a lump containing approximately equal numbers, A, each of u, d and s quarks, might be lighter than a conventional nuclear system with the same baryon number A and with mass about $A \times m_p$. The idea is that the price in binding energy that must be paid by an aggregation of identical u and d quarks because of the Pauli exclusion principle may be greater than the mass difference between the s and u or d quarks:

$$E_{\text{Pauli}} > m_s - m_{u,\,d} \approx 150 \text{ MeV}. \tag{1}$$

Whether this is true depends on details of the strong interactions and of hadronic bag properties, which are difficult to compute reliably (Liu & Shaw 1984; Farhi & Jaffe 1984). Maybe quark nuggets with $m = O(10^{55})$ GeV do not exist at all, but if they do their density is probably comparable to that of ordinary nuclear matter:

$$\rho_{\text{q nugget}} = O(1-z)\rho_{\text{nuclear}}. \tag{2}$$

Because $Q_{\text{em}}(\text{u})+Q_{\text{em}}(\text{d})+Q_{\text{em}}(\text{s}) = 0$, and one has almost equal numbers of u, d and s quarks, one expects

$$Q_{\text{em}}\,(\text{nugget}) \ll A(\text{nugget}) \tag{3}$$

What is very unclear is the initial mass function for these quark nuggets. Large, coherently compressed objects may have a very low production rate in the hot early Universe, and it has been argued (Alcock & Farhi 1985) that streaming neutrinos would dissolve nuggets smaller than the horizon size at the epoch of the quark–hadron phase transition. This would force $A > 10^{55}$! At the other extreme, some calculations (Jaffe 1977) suggest there may be an $A = 2$ state H of strange matter containing 2(uds) which may be lighter than a hyperon plus a proton, and conceivably even lighter than two protons. In the former case, the H would be stable against single β-decay. Its lifetime for double β-decay would be long enough for it to reach Earth from Cygnus X-3 and perhaps produce the muons seen in some proton decay experiments (for a review, see De Rújula 1985*b*). If the H were lighter than two protons, you might think it would be a possible dark-matter candidate. However, because it has strong interactions, it should bind to ordinary matter, and none has been seen in the form of anomalous heavy isotopes (Smith & Bennett 1979; Smith *et al.* 1982). Various other ways to search for strange matter have been proposed (De Rújula & Glashow 1984; De Rújula 1985*a*), notably as a penetrating component in the cosmic rays.

However, I am not very optimistic that there could be enough quark nuggets or strange matter to provide the bulk of the dark matter.

3. Electroweak nuggets

Under very extreme conditions, the gauge bosons of electroweak gauge theory might condense. As is already known from other non-perturbative studies in the Weinberg–Salam model ('t Hooft 1976), baryon and lepton numbers would not be conserved in the neighbourhood of such an electroweak nugget. Thus one could in principle have a state containing many fermions, but with mass less than the corresponding number of baryons (Rubakov 1985). Such a condensate of gauge bosons, quarks and leptons would have a density

$$\rho_{\text{ew nugget}} = O(10^{12})\,\rho_{\text{nuclear}}. \tag{4}$$

Again I doubt that such a coherent field configuration would be copiously produced in the hot early Universe. Many of the above remarks about the detection of quark nuggets would also apply to these electroweak nuggets.

4. Plancktons

These are stable particles with masses $O(m_{\text{p}}) = O(10^{19})$ GeV. Clearly a very powerful conservation law is required to keep such a massive object absolutely stable, and the only candidate is an exact gauge symmetry such as the U(1) of electromagnetism. Indeed, in some versions of the superstring there are (Wen & Witten 1985) stable, free, unconfined particles with fractional electromagnetic charge

$$Q/Q_{\text{e}} = 1/n, \tag{5}$$

where n is an integer that has no particular reason to be three. Because plancktons have masses $O(m_P)$, they can only be copiously produced when the temperature T of the Universe is $O(10^{19}\ \text{GeV}) = O(10^{32})$ K. Our ignorance of this epoch makes it impossible to calculate their abundance reliably.

You might think that such objects could be detected as fractional charges on Niobium balls, but their enormous mass:charge ratio probably means that such plancktons would not be captured on them, but would fall through the Earth. The place to look for them would presumably be in the cosmic rays.

5. MAGNETIC MONOPOLES

You all know what a magnetic monopole is, and that it is predicted (Polyakov 1974; 't Hooft 1974) to be present in any unified gauge theory with some high-energy simple group G (such as SU(5), SO(10) or E_6) broken down to $U(1)_{em}$ at low energies. The monopole mass is predicted to be

$$m_M = O(1/\alpha)\, m_V, \tag{6}$$

where m_V is the mass of the gauge bosons at the first stage of G symmetry breaking, providing the estimate $m_M = O(10^{16})$ GeV in minimal grand unified theories (GUTS). This prediction could be increased, for example in supersymmetric GUTS, to $O(10^{18})$ GeV, in which case monopoles begin to merge with plancktons. Indeed, other theories that are not conventional GUTS but nevertheless incorporate electromagnetic charge quantization also predict monopoles. An example is conventional Kaluza–Klein unification in higher dimensions, for which $m_M = O(m_P)$ (Gross & Perry 1983). Superstring theories provide a new twist, in that their monopoles can have larger magnetic charges

$$Q_M/Q_{\text{Dirac}} = n, \tag{7}$$

where the model-dependent integer n is the same as in the fractional electric charge (5) (Wen & Witten 1985).

It is well known that traditional cosmological theory predicted too many monopoles (Preskill 1979), whereas the new, inflationary universe model (Guth 1981; Linde 1982; Albrecht & Steinhardt 1982) predicts too few to be detected. Astrophysical arguments such as the persistence of large-scale magnetic fields (model-independent) (Parker 1970; Turner *et al.* 1982) or the persistence of neutron stars despite monopole catalysis of baryon decay (model-dependent) (Kolb *et al.* 1982; Dimopoulos *et al.* 1982) strongly suggest there are too few monopoles to provide an interesting amount of dark matter.

However, we should beware of writing monopoles off prematurely. Recently a second candidate has been seen in an induction experiment (D. Caplin *et al.* personal communication 1985) and efforts to detect monopoles by this and other traditional techniques continue to be actively pursued.

6. SHADOW MATTER

This is a new class of particles interacting with ordinary matter through gravitation alone. The masses of individual shadow particles and their relic cosmological density are therefore very model dependent. Recent interest in shadow matter has been triggered by the superstring

(Ellis 1985), which contains gauge interactions of the form E_8 (for ordinary matter) × E'_8 (for shadow matter), which are linked only via gravitational and other couplings of $O(1/m_P)$. The masses of the shadow particles would be around the scale at which the new shadow gauge forces become strong. Unfortunately, we do not know what this might be. Shadow matter could be a suitable dark-matter candidate if the lightest shadow particle were stable (Kolb *et al.* 1985). However, I see no particular reason to expect this to be the case and in most superstring scenarios the hidden and observable sectors have very different dynamics (Dine *et al.* 1985; Cohen *et al.* 1985).

In view of its unknown properties, calculating the relic cosmological density of shadow matter is impossible, and there is no particular reason to expect it to be large. There is certainly no justification for thinking that the shadow particle masses and density should be the same as those of conventional matter.

Detecting shadow matter is only possible through its gravitational effects. It cannot shine in any part of the electromagnetic spectrum, because photons are included in the observable, not hidden, E_8 of gauge interactions. In principle, if stable shadow matter existed it would form shadow galaxies, perhaps stars, etc. Shadow matter could even be passing through us all the time and we would not know it! Enticing though it may be to speculate about shadow matter, I do not find it very convincing.

7. SUPERSYMMETRIC DARK-MATTER CANDIDATES

These are the ones that I find the most motivating, and have worked on the most, so I will discuss them in more detail than other candidates.

7.1. *The nature of supersymmetric relics*

Most supersymmetric theories contain one absolutely stable particle and one very long-lived particle, which may also be an important cosmological relic. The stable particle arises because most supersymmetric theories have a multiplicatively conserved quantum number called R parity (Fayet 1980), which is +1 for conventional particles and −1 for their supersymmetric partners. R parity is clearly conserved by the interaction vertices in supersymmetric gauge theories:

$$g(\bar{f}fV, \bar{f}\tilde{f}\tilde{V}); \quad \lambda(\bar{f}fH, \bar{f}\tilde{f}\tilde{H}); \quad g^2|\bar{\tilde{f}}\tilde{f}|^2; \quad \lambda^2|\tilde{f}^2|^2; \text{ etc.} \tag{8}$$

R parity could be violated spontaneously by a vacuum expectation value for a sparticle $\tilde{X}$: $\langle 0|\tilde{X}|0\rangle \neq 0$, of which the most obvious possible example would be a sneutrino $\tilde{\nu}$. However, $\langle 0|\tilde{\nu}|0\rangle \neq 0$ also violates lepton number, and hence is very tightly constrained. Moreover, most models do not predict $\langle 0|\tilde{\nu}|0\rangle \neq 0$, and R parity conservation is the generic expectation. This has three important phenomenological consequences: (*a*) sparticles are always produced in pairs, e.g. $e^+e^- \to \tilde{e}^+\tilde{e}^-$ or $\bar{p}p \to \tilde{q}\tilde{g} + X$; (*b*) heavier sparticles decay into lighter sparticles, e.g. $\tilde{e} \to e\tilde{\gamma}$, $\tilde{q} \to q\tilde{g}$, $\tilde{g} \to q\bar{q}\tilde{\gamma}$, and (*c*) the lightest sparticle must be absolutely stable, because it has no legal way to decay. This is the expected stable supersymmetric relic (Ellis *et al.* 1984*a*).

Also possible is a long-lived relic. Because the gravitino is closely related to the graviton, it has only very weak couplings proportional to $1/m_p$, such as

$$(1/4M)\,\bar{\lambda}^a\gamma^M\sigma^{\rho\sigma}\psi_\mu F^a_{\rho\sigma} \quad \text{for gauge fields;}$$

$$(1/2M)\,\bar{\psi}_\mu\gamma z^*_i\gamma^M f^i_L \quad \text{for matter fields,} \tag{9}$$

where
$$M \equiv m_{\mathrm{P}}/\sqrt{(8\pi)}.$$

Therefore, if the gravitino is not the lightest sparticle, but is not very heavy, it must be long-lived:

$$\Gamma(\psi_\mu \to \gamma + \tilde{\gamma}) \approx m_{\frac{3}{2}}^3/4m_{\mathrm{P}}^2, \text{ etc.} \tag{10}$$

corresponding to (Cohen *et al.* 1985)

$$\tau(\tfrac{3}{2} \to \mathrm{V} + \tilde{\mathrm{V}}, \phi^{\mathrm{i}} + \tilde{\phi}_{\mathrm{i}}) \approx \frac{4 \times 10^8 \text{ s}}{12 + 2N_\phi} \times \left(\frac{100 \text{ GeV}}{m_{\frac{3}{2}}}\right)^3, \tag{11}$$

where N_ϕ is the number of matter species with mass less than $m_{\frac{3}{2}}$. Indeed, (11) tells us that

$$\tau(\tfrac{3}{2} \to \text{all}) > 100 \text{ s} \quad \text{if} \quad m_{\frac{3}{2}} < \frac{7.4 \text{ TeV}}{(12 + 2N_\phi)^{\frac{1}{3}}} \tag{12}$$

so that the gravitino may well decay after primordial nucleosynthesis. If the gravitino is actually the lightest sparticle, so that by the previous argument it is absolutely stable, then the next-to-lightest sparticle must be long lived, because its only available decay is via one of the small couplings (9).

Thus we expect one stable supersymmetric relic and one long-lived one.

7.2. *The nature of the stable supersymmetric relic*

This cannot have either electromagnetic or strong interactions for, if it did, it would condense along with ordinary matter into galaxies, stars, planets, etc. In this case it should have shown up in searches for anomalous superheavy isotopes, for whose abundance there is an upper limit (Smith & Bennett 1979; Smith *et al.* 1982)

$$n_{\text{relics}}/n_{\text{protons}} < O(10^{-20}\text{–}10^{-30}) \tag{13}$$

for 3 GeV $< m_{\text{relic}} <$ 10^3 GeV. This conflicts with the abundance calculated in conventional Big-Bang cosmology (Wolfram 1979; Dover *et al.* 1979):

$$n_{\text{relics}}/n_{\text{protons}} \propto \frac{1}{\sigma(\mathrm{R}\bar{\mathrm{R}} \to \mathrm{X})} \sim O(10^{-10}/\alpha^2), \tag{14}$$

which becomes $O(10^{-10})$ for strongly interacting relics, and $O(10^{-6})$ or more for weakly or electromagnetically interacting relics. We therefore conclude that the stable supersymmetric relic must be electromagnetically neutral and only have weak interactions. The available candidates are

$$\left.\begin{array}{llllll} \text{spin:} & 0 & \frac{1}{2} & 1 & \frac{3}{2} \\ \text{sparticle:} & \tilde{\nu} & \tilde{\gamma}, \tilde{\mathrm{H}}^0 & \text{—} & \text{gravitino} \end{array}\right\} \tag{15}$$

in order of increasing spin, and the likely abundances of each of them can be estimated.

Sneutrino $\tilde{\nu}$

The $\tilde{\nu}\bar{\tilde{\nu}}$ annihilation cross section is almost unknown, with light neutral spin $\frac{1}{2}$ sparticles dominating the amplitudes and leading to $\nu\bar{\nu}$ final states. For suitable choices of the neutral mass parameters, the relic $\rho_{\tilde{\nu}}$ can be brought below the closure density (taken to be $\rho_{\mathrm{c}} = 2 \times 10^{-29}$ g cm^{-3} corresponding to a present Hubble expansion rate of $H_0 = 100$ km s^{-1} Mpc^{-1}) for any value of $m_{\tilde{\nu}}$ (Ibáñez 1984; Hagelin & Kane 1984). However,

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in most theoretical models, the possibility $m_{\tilde{\nu}} < m_{\tilde{\gamma}}$ or $m_{\tilde{\mathrm{H}}^0}$ looks contrived. Moreover, it has been argued that if $\tilde{\nu}$ formed the dark matter, some of them would be captured inside the Earth and annihilate there to give a ν flux considerably larger than that allowed by the proton stability experiments (Freese 1985).

Photino $\tilde{\gamma}$

These could have a relic density less than the closure density for

$$m_{\tilde{\gamma}} \geqslant \tfrac{1}{2}\ \mathrm{GeV}\ (\text{if } m_{\tilde{\mathrm{f}}} \approx 20\ \mathrm{GeV}) \quad \text{to} \quad m_{\tilde{\gamma}} \geqslant 5\ \mathrm{GeV}\ (\text{if } m_{\tilde{\mathrm{f}}} \approx 100\ \mathrm{GeV}) \tag{16}$$

(Goldberg 1983; Ellis *et al.* 1984*a*), which is a plausible range from the point of view of models.

Higgsino $\tilde{\mathrm{H}}^0$

Their annihilation cross section is smaller than that for photinos, but they could have a relic density less than the closure density if

$$m_{\tilde{\mathrm{H}}^0} \geqslant m_{\mathrm{b}}\ (\text{if } m_{\tilde{\mathrm{f}}} \approx 20\ \mathrm{GeV}) \quad \text{to} \quad m_{\tilde{\mathrm{H}}^0} \geqslant m_{\mathrm{t}}\ (\text{if } m_{\tilde{\mathrm{f}}} \approx 100\ \mathrm{GeV}) \tag{17}$$

(Ellis *et al.* 1984*a*) in which case their larger annihilation rate to heavier quarks suppresses their number density adequately. Another possibility would be that

$$m_{\tilde{\mathrm{H}}^0} \lesssim O(100\ \mathrm{eV}), \tag{18}$$

in which case their annihilation rate via the Z^0 is sufficient, as has long been known to be the case with conventional neutrinos. However, in the light $\tilde{\mathrm{H}}^0$ case (18) there is the danger of an approximate symmetry which would lead to a light axion-like particle which is excluded by experiment (Ellis *et al.* 1984*a*).

The above results on spin-$\frac{1}{2}$ supersymmetric relic candidates are refined in an interesting way if one uses the minimal supergravity model relations for the renormalized $\tilde{\mathrm{f}}$, $\tilde{\gamma}$ and $\tilde{\mathrm{g}}$ masses in models for which the $\tilde{\gamma}$ is the lightest sparticle. In this case (1) the relic density is less than the closure density for $H_0 = 50\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$, namely $\rho_{\mathrm{c}} = 5 \times 10^{-30}\ \mathrm{g\ cm^{-3}}$, only if

$$m_{\tilde{\mathrm{q}}} \lesssim 0.8\, m_{\tilde{\mathrm{g}}} + 40\ \mathrm{GeV} \tag{19}$$

(Ellis *et al.* 1985*b*) and (2) the lightest charged sparticle the $\tilde{\mathrm{l}}^{\pm}_{\mathrm{R}}$ weighs more than the experimental lower limit of 20 GeV only if (Ellis *et al.* 1985*b*)

$$\rho > O(10^{-2})\, \rho_{\mathrm{c}}. \tag{20}$$

Thus minimal supergravity models *require* that dark matter must be present with a non-negligible relic density.

Gravitino $\frac{3}{2}$

This, the last of the supersymmetric candidates (19), behaves in a rather different way from the others. The very small couplings (9) mean that its primordial abundance is not significantly reduced by subsequent annihilations. If its relative abundance is not suppressed by any subsequent epoch of entropy generation such as inflation, the present number density of stable gravitinos is somewhat less than that of neutrinos, so a more relaxed analogue of (18) applies, namely (Pagels & Primack 1982),

$$m_{\frac{3}{2}} \lesssim O(1)\ \mathrm{keV}. \tag{21}$$

However, the primordial abundance can be significantly suppressed by inflation (Ellis *et al.* 1982), after which $X\tilde{X}\rightarrow\frac{3}{2}+\ldots$ collisions with cross sections $\sigma\propto1/m_{\mathrm{P}}^2$ regenerate a gravitino number density (Ellis *et al.* 1984*b*)

$$n_{\frac{3}{2}}(T)=3.35\times10^{-2}\,T^3(T_{\mathrm{r}}/10^9\ \mathrm{GeV})\,[1-0.018\ln(T_{\mathrm{r}}/10^9\ \mathrm{GeV})],\qquad(22)$$

where T is the effective gravitino temperature and T_{r} is the temperature of reheating after the inflation ends. In this case the upper bound (21) on the stable gravitino mass is replaced by (Ellis *et al.* 1985*a*)

$$m_{\frac{3}{2}}\lesssim100\ \mathrm{GeV}\times(1.3\times10^{12}\ \mathrm{GeV}/T_{\mathrm{r}}).\qquad(23)$$

This bound is not incompatible with a stable gravitino with mass $O(10^2)$ GeV and baryosynthesis by intermediate mass Higgses subsequent to inflation. However, an unstable gravitino seems more likely in most supergravity models.

7.3. *Detection of stable relics*

Annihilation in the galactic halo

The archetype for this process is $\tilde{\gamma}\tilde{\gamma}\rightarrow\bar{\mathrm{p}},\ \mathrm{e}^+,\ \gamma+\mathrm{X}$ (Silk & Srednicki 1984). In general, one finds that $\tilde{\gamma}\tilde{\gamma}\rightarrow\bar{\mathrm{p}}+\mathrm{X}$ is potentially observable if $m_{\tilde{\mathrm{f}}}$ is *ca.* 50–60 GeV, whereas $\tilde{\mathrm{H}}^0\tilde{\mathrm{H}}^0\rightarrow\bar{\mathrm{p}}+\mathrm{X}$ could be observable if the ratio of supersymmetric Higgs vacuum expectation values $v/\bar{v}\gtrsim2$, although $\tilde{\nu}\tilde{\nu}\rightarrow\bar{\mathrm{p}}+\mathrm{X}$ is probably unobservable because sneutrinos mainly annihilate into $\nu\bar{\nu}$ (Hagelin & Kane 1985; Stecker *et al.* 1985). In the following table 1, fluxes of $\bar{\mathrm{p}}$, e^+ and γ are quoted for a sample $\tilde{\gamma}$ model with

$$\left.\begin{aligned}m_{\tilde{\mathrm{l}}}=50\ \mathrm{GeV};\quad m_{\tilde{\mathrm{q}}}=100\ \mathrm{GeV},\quad m_{\tilde{\gamma}}=4.2\ \mathrm{GeV}\\ \langle\sigma v\rangle=8.5\times10^{-29}\ \mathrm{cm^3\,s^{-1}},\quad\rho_{\mathrm{c}}=5\times10^{-30}\ \mathrm{g\,cm^{-3}}\end{aligned}\right\}\qquad(24)$$

together with high and low estimates to get some ideas of the likely ranges, and some observed fluxes. We see that the stable supersymmetric relic annihilation could well yield fluxes close to the observed ones.

TABLE 1. POSSIBLE STABLE PARTICLE FLUXES FROM $\tilde{\gamma}\tilde{\gamma}$ ANNIHILATION IN THE GALACTIC HALO (HAGELIN & KANE 1985)

particle	sample model flux $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$	high flux $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$	low flux $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$	observed flux $\mathrm{cm^{-2}\,s^{-1}\,sr^{-1}}$
$\bar{\mathrm{p}}$	1.1×10^{-6}	6×10^{-5}	10^{-7}	3×10^{-6}
e^+	3×10^{-4}	10^{-3}	3×10^{-6}	1×10^{-3}
γ	0.9×10^{-7}	7×10^{-7}	10^{-9}	varies with E_γ

Annihilation in the solar system

In contrast with the case of $\tilde{\nu}\tilde{\bar{\nu}}$ annihilation discussed earlier, $\tilde{\gamma}\tilde{\gamma}$ or $\tilde{\mathrm{H}}^0\tilde{\mathrm{H}}^0$ annihilation inside the Earth gives unobservably few neutrinos. Likewise, annihilation in other planets of the Solar System such as Uranus is also unobservable (Krauss *et al.* 1985*a*). Annihilation of photinos inside the Sun could produce $O(2)$ ν interactions per kilotonne-year in a proton-stability experiment (Silk *et al.* 1985), which is probably also too few to be picked out of the background by present-day detectors.

Laboratory experiments

If photinos form the dark matter in galactic halos, we live in a bath of $\tilde{\gamma}$ with velocities $O(200 \text{ km s}^{-1})$. These can scatter elastically on the nuclei (Z, A) of conventional matter, depositing a recoil kinetic energy

$$E \approx 2m_{\tilde{\gamma}}^2 v^2 / m_{(Z,A)}. \tag{25}$$

Unfortunately, because photinos are Majorana particles, they only have spin-dependent interactions with nuclei, and no coherent interaction. The rate for such collisions has been estimated as (Goodman & Witten 1984)

$$R_{\text{coll}} = \left(\frac{1.1 \text{ events}}{\text{kg d}}\right)\left(\frac{100 \text{ GeV}}{m_{\tilde{\text{q}}}}\right)^4 \left(\frac{4m_{\tilde{\gamma}}\, m_{(Z,A)}}{m_{\tilde{\gamma}} + m_{(Z,A)}}\right)^2 \left(\frac{q}{\frac{2}{3}e}\right)^4 \times \lambda^2 J(J+1) \left(\frac{\rho_{\text{halo}}}{10^{-24} \text{ g cm}^{-3}}\right)\left(\frac{\langle v \rangle}{200 \text{ km s}^{-1}}\right), \tag{26}$$

where the $\tilde{\gamma}$ is assumed to interact with quarks of charge q in the nucleus (Z, A) via squarks with mass $m_{\tilde{\text{q}}}$. The factor $\lambda^2 J(J+1)$ depends on nuclear physics, and takes the favourable values 0.42 for ^{27}Al and 0.50 for ^{69}Ga or ^{71}Ga. Equation (26) suggests that observable rates could be obtained with even a small detector. The typical nuclear recoil energy would be $O(1)$ keV for $m_{\tilde{\gamma}} = O(4)$ GeV. Among detectors proposed are superconducting colloids (Drukier & Stodolsky 1984), wires or filaments (Smith discussion following paper by Jelley, this symposium), and supercooled silicon blocks or wafers (Cabrera *et al.* 1985). In the case of the colloid proposal, small superconducting grains are embedded in a target medium. When stable relics scatter in this medium, they produce phonons which may hit one of the small superconducting grains, heating it up so that it goes normal. The whole device is placed in a magnetic field, whose perturbation by this transition can be picked up by a squid. Ideas to detect supersymmetric dark matter candidates are discussed further in this symposium by Jelley and Smith.

7.4. *Unstable relics*

Recall that the gravitino (if it is not the lightest sparticle) or the next-to-highest sparticle (if the gravitino is the lightest) is expected to decay after primordial nucleosynthesis if it has mass less than a few teraelectronvolts as expected in many models. This leads to difficulties with the mass density during nucleosynthesis, entropy generation after nucleosynthesis, the photodissociation of light elements, and a possible distortion of the cosmic microwave background radiation. The constraints these impose on the gravitino abundance and on the reheating temperature after inflation are listed in table 2. We see that the tightest constraint

TABLE 2. BOUNDS ON UNSTABLE GRAVITINOS (ELLIS *ET AL.* 1985*a*; LINDLEY 1985)

constraint	bound on abundance	bound on reheating temperature
mass density during nucleosynthesis	$n_{\frac{3}{2}}/n_{\gamma} < 1.6 \times 10^{-6}(100 \text{ GeV}/m_{\frac{3}{2}})$	$T_{\text{r}} < 9.3 \times 10^{15}(100 \text{ GeV}/m_{\frac{3}{2}})$ GeV
entropy generation after nucleosynthesis	$< 2.4 \times 10^{-8}(m_{\frac{3}{2}}/100 \text{ GeV})^{\frac{1}{2}}$ (for $\frac{3}{2} \rightarrow \gamma + \tilde{\gamma}$, $m_{\frac{3}{2}} < 700$ GeV)	$< 1.3 \times 10^{14}(m_{\frac{3}{2}}/100 \text{ GeV})^{\frac{1}{2}}$ GeV
photodissociation of light elements	$< 6.2 \times 10^{-14}(100 \text{ GeV}/m_{\frac{3}{2}})$	$< 2.5 \times 10^{8}(100 \text{ GeV}/m_{\frac{3}{2}})$ GeV
distortion of the microwave background ($\mu < 8 \times 10^{-3}$)	$< 5.5 \times 10^{-12}(m_{\frac{3}{2}}/100 \text{ GeV})^{\frac{1}{2}}$	$< 5.1 \times 10^{10}(m_{\frac{3}{2}}/100 \text{ GeV})^{\frac{1}{2}}$ GeV

is generally provided by the photodissociation of light elements, though distortion of the microwave background can become important for a gravitino with mass of a few giga-electronvolts. Improvements in the already impressive upper bounds on a chemical potential for the microwave background radiation would further enhance the competitivity of these bounds.

8. Massive neutrinos

It is well known that conventional abundance calculations have led to two allowed regions for the masses of neutrinos with conventional weak interactions, namely

$$\sum_{\mathrm{v}} (\tfrac{1}{2}g_{\mathrm{v}})\, m_{\mathrm{v}} \leqslant 100\ \mathrm{eV}\ (\rho/\rho_{\mathrm{c}})\ (H_0/100\ \mathrm{km\ s^{-1}\ Mpc^{-1}})^2 \tag{27}$$

and (Lee & Weinberg 1977)

$$m_{\mathrm{v}} \geqslant \begin{cases} 4.9\text{–}13\ \mathrm{GeV} & \text{for Majorana neutrinos} \\ 1.3\text{–}4.2\ \mathrm{GeV} & \text{for Dirac neutrinos,} \end{cases} \tag{28}$$

where the values (28) are from a recent reevaluation (Kolb & Olive 1985), and the quoted spreads in the lower bounds correspond to $H_0 = 100\text{–}50\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$. Neutrinos with unconventional weak interactions could give the closure density even if their masses are between the limits (27)–(28) (Kolb & Turner 1985).

There is no exact conservation law to fix $m_{\mathrm{v}} = 0$, and theorists generally expect $m_{\mathrm{v}} \neq 0$. As has been described in this symposium, there is no confirmed experimental evidence that $m_{\mathrm{v}} \neq 0$, whereas the masses of the neutrinos are very model-dependent. On the other hand, the number density of massive neutrinos is reliably calculable, once their weak interactions are specified.

The sorts of detectors discussed in the previous section would work equally well for neutrinos of mass $O(\mathrm{GeV})$. Neutrinos of mass between $O(1)$ and 100 eV can be detected by looking carefully at β-decay spectra, but detecting cosmological relic neutrinos in this mass range seems nigh to impossible. Searches for neutrino oscillations offer an indirect way to look for differences in neutrino masses, provided their mixing angles are sufficiently large. However, there is no guarantee that dark matter in the form of neutrinos could be detected in the laboratory.

9. Axions

It is well known that axions are almost massless pseudoscalar bosons (Peccei & Quinn 1977; Weinberg 1978; Wilczek 1978), postulated to solve the strong CP problem, with masses

$$m_{\mathrm{a}} = O(100\ \mathrm{MeV})^2/f_{\mathrm{a}} \tag{29}$$

and pseudoscalar couplings

$$g_{\mathrm{af\bar{f}}} = m_{\mathrm{f}}/f_{\mathrm{a}} \tag{30}$$

to fundamental fermions, where f_{a} is a model-dependent scale parameter. They also have couplings $O(\alpha/f_{\mathrm{a}})$ to pairs of photons. Particle-physics experiments exclude $f_{\mathrm{a}} < O(300)$ GeV, whereas astrophysics excludes f_{a} below $O(10^9)$ GeV. This improved lower bound comes from a recent and more detailed study of the energy flow in red-giant stars (G. Steigman personal communication 1985). To keep the cosmological density of coherent axion waves below the closure density, one must choose $f_a < O(10^{12})$ GeV. The range between these bounds is that of the 'invisible' axion, so called because it was supposed to be undetectable in particle physics experiments.

However, Sikivie (1983) has proposed ways in which galactic halo axions could be detected in the laboratory. One idea is that galactic-halo axions in an inhomogeneous magnetic field could produce observable microwave photons, whereas another is that the Q of a microwave cavity could change as it is tuned through the frequency corresponding to the axion mass. Axions emitted by the Sun could also be detected by their emission of X-ray photons in an inhomogeneous magnetic field. It has also been proposed (Krauss *et al.* 1985*b*) that axions may have observable interactions with the polarized electrons in ferrites which produce photons. Although more work on these proposals is necessary, it seems possible that axions with a coherent wave density close to the closure density could be detected in the laboratory.

10. POLONYIONS

These are light scalars with masses $O(m_W^2/m_P)$ which appear in supergravity theories. They would also form coherent waves, which in most models have a density far above the closure density (Holman *et al.* 1984; Goncharov *et al.* 1984). The polonyion density can be adjusted to be cosmologically acceptable, though not in a very natural way (Coughlan *et al.* 1984; Ovrut & Steinhardt 1984). The polonyions are not strongly coupled to fundamental fermions, but have couplings $O(1/m_P)$ to pairs of photons. These are too weak to be seen in the experiments discussed in the previous section. Perhaps we had better hope that they are not the dark matter.

11. SUMMARY

There is clearly no shortage of particle candidates for dark matter, but no consensus as to which is the most plausible. Most of them would provide cold dark matter. There is no good reason why most of the candidates should have a density close to the closure density, but supersymmetric relics are an exception. The general feature that their individual masses are not greatly different from those of baryons, unlike, say, plancktons or polonyions, gives one reason to hope that perhaps $\rho_{\tilde{\gamma}} \approx \rho_{\text{baryons}}$, and hence that the supersymmetric relic density may not be much less than the closure density. Indeed, we have seen that $\rho_{\tilde{\gamma}} \gtrsim O(10^{-2})\,\rho_c$ in a class of minimal supergravity models. Moreover, supersymmetric relics are theoretically well motivated, and relatively easy to detect. Supersymmetric particles should also be accessible to accelerator searches in general. Thus they offer the best prospects for rapid experimental progress on dark matter. The time is approaching when the study of dark matter should evolve from a province of theory and astrophysics to become an experimental subject.

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