group of the pigment molecule[15,16]. By manipulating his own body temperature by only one degree, the physicist De Vries was able to demonstrate changes in his visual sensitivity to the far red[17]. Temperature variations of this order occur diurnally; in women there is a monthly variation. If Neitz and Jacobs' young men did cluster at two temperatures, it would be easy to explain why the bimodality was obscured in their young women.

But suppose there is a polymorphism of the long-wave pigment. Has it been maintained by a heterozygous advantage? In the squirrel monkey, a basically dichromatic species, there is almost certainly a polymorphism at the single locus that specifies a pigment in the red–green spectral region[18,19]. Heterozygous females become behaviourally trichromatic[20] because X-chromosome inactivation[21] segregates into different cones the products of the alternative alleles; the monkey's visual system seems plastic enough to exploit this added differentiation of cone cells. It has been suggested that the polymorphism is in fact maintained by the advantage to the heterozygous females[18]. Our own species is basically trichromatic. So if many women are heterozygous for one of the photopigments, are they in fact tetrachromatic, enjoying an extra dimension of colour discrimination? And if they are, does it give them an advantage? ☐

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Grand unification

Solar neutrinos may hold the key

from Lincoln Wolfenstein

THE question of the mass of the neutrino has been of great interest from Fermi's first analysis of nuclear beta decay to the present. There is still no confirmed evidence that neutrinos have a non-zero mass. However, laboratory experiments cannot probe for the very small masses that are suggested by many theories. Recently, great interest has arisen in the possibility that experiments searching for neutrinos from the Sun may prove the best way to probe neutrino mass.

A class of theories called grand unified theories treat the electron, its neutrino ν_e and the quarks that make up the nucleon as different states of a single particle. In the simplest of these theories the small neutrino mass is given by the 'see-saw' formula $m_\nu = m_D^2/M$, where m_D is the quark or electron mass and M is a mass which may be as large as the unification scale of 10^{14} to 10^{15} GeV. There are three sets, or generations, of particles. Thus in addition to the electron, there is the muon ($m_\mu = 206m_e$) and the τ particle ($m_\tau = 3{,}500m_e$). Correspondingly there are three neutrinos, ν_e, ν_μ and ν_τ. The theory suggests $m(\nu_e) << m(\nu_\mu) << m(\nu_\tau)$.

A method of investigating small neutrino masses is a search for neutrino oscillations. This is based on the idea that ν_e, ν_μ and ν_τ are coherent mixtures of the three neutrino mass eigenstates, in direct analogy with the quarks, where whatever causes the masses of particles mixes the eigenstates seen by the weak interaction. In the case of quarks, this mixing was first described by the Cabbibo angle. In the case of neutrinos, the electron neutrino ν_e, for example, the neutrino produced in nuclear beta decay, might be $\nu_1\cos\theta + \nu_2\sin\theta$, where ν_1 and ν_2 are the mass eigenstates and θ is the mixing angle. As the neutrino propagates through the vacuum, the phase of ν_2 changes relative to ν_1 as a result of their mass difference. Thus the neutrino is no longer a pure ν_e; elementary quantum mechanics gives the probability that it is still ν_e as an oscillating function with a minimum of $\cos^2 2\theta$. In quantum mechanics the same type of analysis describes the precession of a spin-½ magnet oriented at an angle 2θ to the magnetic field.

Many experiments at accelerators and reactors have looked for such oscillations without success. If M in the see-saw formula is greater than 10^{11} GeV the masses become very small and the distance needed for oscillations is much larger than is available in the laboratory. The theory further suggests that θ is 10° or less, so that the amplitude of vacuum oscillations is small.

Recently S.P. Mikhaeyev and A. Yu Smirnov pointed out that even with small values of θ very large oscillations can occur for neutrinos moving outward from the centre of the Sun. Their work (*Nuovo Cimento* **9**C, 17; 1986) is based on my own earlier observation that neutrino oscillations in matter are modified from those in vacuum as a result of the index of refraction associated with the forward scattering of ν_e from electrons. They point out that neutrinos may pass through a region with a density such that the mixing angle in matter reaches 45° even though the vacuum θ is as small as 1°.

Over the past 20 years Ray Davis has been detecting solar neutrinos via the inverse beta-decay of ^{37}Cl. The flux observed appears to be one-quarter to one-half that expected on the basis of standard solar model calculations. This result is explained by Mikhaeyev and Smirnov by the conversion of the missing neutrinos into ν_μ or ν_τ by the enhanced oscillation effect inside the Sun. This effect depends on the energy of the neutrinos. Davis' experiment is primarily sensitive to the high-energy ν_e from the decay of ^{8}B (end-point energy 14 MeV). Experiments using a gallium detector now being planned in Europe and the Soviet Union will look for the much more common low-energy neutrinos from the fundamental thermonuclear reaction $p + p \rightarrow d + \nu_e + e$ (where p is a proton, d a deuteron and e an electron). According to the oscillation theory the result of the gallium experiment depends on the neutrino mass. For a mass of the heavier neutrino (into which ν_e oscillates) of 10^{-2} eV the gallium result would agree with the standard solar model, while for lower masses the ν_e flux would be suppressed by a factor reaching 10 for a mass of 3.10^{-4}eV.

If there is no suppression of these low-energy neutrinos, an alternative explanation of Davis' result is a slight reduction in the central temperature of the Sun which can cause a large decrease in the amount of ^{8}B in the Sun but does not affect the p–p neutrinos. The alternative can be distinguished by a measurement of the ^{8}B neutrinos, which would be greatly distorted in the oscillation scenario. A large liquid argon detector (called Icarus) proposed for the laboratory in the Gran Sasso tunnel in Italy by a team including Carlo Rubbia could measure this spectrum for 6 to 14 MeV. Another group propose detecting this spectrum using heavy water in a planned laboratory in a mine in Ontario, Canada.

A more dramatic way to confirm the oscillation scenario would be to detect the ν_μ or ν_τ into which the ν_e is converted. Such detection depends on the neutral current interaction and is more difficult. One possibility is to detect neutrino–electron scattering events in a detector like Icarus in an energy region where the ν_e has been found to be highly suppressed. In the heavy-water detector the neutral current interaction could result in the disintegration of the deuteron into neutron plus proton.

Measurements of the solar neutrino flux at different energies could distinguish between explanations of Davis' experiments. Whether or not the Mikhaeyev–Smirnov analysis is the correct explanation, the solar neutrino experiments can give information on neutrino mass in the range 10^{-2} to 10^{-4} eV and thus to values of M in the see-saw formula between 10^{11} and 10^{15} GeV. Thus it is hoped to obtain information on neutrino masses over a range inaccessible to experiments at accelerators and reactors. ☐

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