with changes in the function of Hox genes. One implication of these results is that the independent evolution of similar types of appendage in crustaceans may have involved similar changes in regulatory gene function. This poses a ‘chicken and egg’ problem for palaeontologists: if independent evolution of key characters is common, how is phylogeny to be reconstructed? A way out of this quandary will probably only come from understanding the biological basis of the features that we use to reconstruct evolutionary history. □

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Particle physics

The Standard Model transcended

Frank Wilczek

Prolonged applause met Professor Kajita’s presentation last month[*] of results from the SuperKamiokande detector[1]. After decades of ardent searching, marked by numerous false alarms and several tantalizing but precarious hints, a physical phenomenon lying beyond the framework of the Standard Model of physics had been clearly identified. Neutrinos have mass.

The new observations concern the different types of neutrino (electron, muon and tau) produced by cosmic rays in the Earth’s atmosphere, and they strengthen earlier indications[2] that there are fewer muon-type neutrinos than expected. In the details of its dependence on energy and angle, this anomaly is consistent with a very specific hypothesis: muon neutrinos are a mixture of two states with different masses. As time progresses, the theory goes, these two states fall out of phase; then the proportions of the mixture have changed, and no longer fit the specifications for a muon neutrino. The new mixture is part muon neutrino, part something else (probably a tau neutrino) — the muon neutrino has ‘oscillated’.

The extent of the oscillation should depend in a very specific way on the difference between the masses, the original proportions of the mixture, the neutrino’s energy and the distance it has travelled. The distance is related to the neutrino’s arrival angle, as it originated in the atmosphere; and the energy is related to the energy released in the detector. The predicted dependence of the oscillation on angle and energy matches the observed anomalies quite well, so it seems appropriate — to the extent that it is ever possible — to claim that the observations ‘rule in’ the hypothesis. The neutrino mass difference needed to explain the observations is minuscule: a few hundredths of an electron volt, or less than 10^{-7} times the mass of the electron.

But the raw phenomena do not begin to convey the discovery’s significance. It cannot be considered as a bizarre, tiny correction to our previous understanding; rather, it is a first step towards a more comprehensive, and much more beautiful, formulation of the fundamental laws of physics. For, as I shall explain, this neutrino mass confirms bold theoretical ideas about symmetry and unification of forces that arise from the deep structure of the Standard Model.

In the Standard Model, the quarks and leptons that are the building blocks of matter fall into five separate classes, or multiplets (Fig. 1). There are ‘strong’ interactions, mediated by colour gluons, which can transform particles within a multiplet; ‘weak’ interactions, mediated by W bosons, that can transform particles between multiplets; and ‘hypercharge’ interactions, mediated by a mixture of photon and Z boson, which leave the particles unchanged (and include the more familiar electromagnetic interaction). It would be difficult to overstate the power and practical success of the Standard Model, but one cannot deny the superficially graceless cast of Fig. 1. Because we are discussing the most basic laws of nature, we have a right to expect better.

Fortunately, postulating a higher degree of symmetry produces a prettier picture[3,4]. One version, called SO(10) symmetry[5], looks especially good in light of the new neutrino mass measurements. In this unified theory (see Box, overleaf), all the particles of the Standard Model appear in one multiplet, and transformations within it include both the strong and weak interactions, now appearing on an equal footing.

The SO(10) unification of matter into one multiplet is a stunning achievement, but there have always been two nagging questions about it. First, one requires an additional particle to complete the symmetry, here called N. Where is it? Second, the postulated symmetry between the strong and weak interaction requires that they have equal power, which is not so.

The predicted properties of N are peculiar. Considering only the interactions of the Standard Model (instead of the full SO(10)), N is completely neutral — it has no strong, weak or electromagnetic interactions. That makes it elusive. Related to this neutrality is a unique feature of N’s mass. Whereas all the other particles would be massless in empty space, and acquire mass only as a result of their interactions with the omnipresent so-called Higgs field, N has an independent mass. Indeed, the interaction of N with the Higgs field converts it into an ordinary neutrino. All potentially observable consequences of the existence of N depend on the value of its mass. Fortunately, insight into this arises from our second nagging question — the inequality between strong and weak forces.

The coupling strength of forces in the Standard Model depends on distance in a precisely calculable way[6,7]. By extrapolating these calculations to much smaller distances — equivalently, much larger energies — we can test the idea that the strong, weak and electromagnetic interactions are different facets of one universal interaction[8]. Remarkably, it works. The various coupling strengths do meet, indicating that unification occurs at distances below 10^{-32} m, or energies above 10^{16} GeV. In comparison, direct measurements currently peter out at around 10^{-18} m, or 100 GeV.

Now I can show how the different strands knit together to produce neutrino masses[9,10]. N’s mass is closely related to the unification scale — a very large mass scale by other standards. Ordinary neutrinos then acquire mass indirectly through their interaction with N: it is possible for a left-handed neutrino (ν) to change into a left-handed N, then a right-handed anti-N, and finally into a right-handed anti-ν (see Box). This process requires a quantum fluctuation to account for the fleeting existence of N and anti-N. But quantum fluctuations to states of such large energy are very rare. So the process whereby ordinary neutrinos flip their handedness, which is a measure of their mass, is heavily suppressed. Quantitatively, this argument

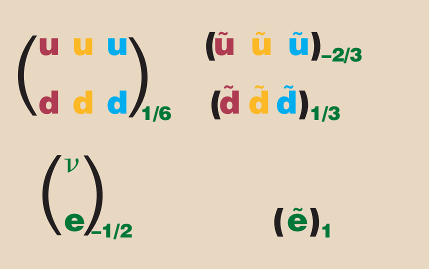

Figure 1 **Multiplets of the Standard Model of particle physics. The up and down quarks, neutrino and electron shown here form only the first particle family (of three). The figure also omits right-handed particles, but the same pattern of five isolated multiplets is repeated for each family and handedness. The strong nuclear interaction transforms particles horizontally; the weak interaction, vertically. The subscript is hypercharge.**

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[*] *Neutrino ’98*, Takayama, Japan, 4–9 June 1998.

predicts neutrino masses of about the value reported by Kajita — which no other current theories do.

What's next? The theory of neutrino masses and mixings is far from complete[2]. The long-standing apparent shortage of neutrinos from the Sun might be explained by oscillations of electron neutrinos, as might a reported anomaly in accelerator neutrino experiments. And neutrinos of large enough mass — about a hundred times the mass difference that SuperKamiokande has measured — could provide a significant 'dark matter' component to the density of the Universe, and so affect the evolution of large-scale structure in galaxy clustering.

Some less direct ramifications may prove still more profound. Unification of couplings seems to require another extension of the Standard Model, to include approximate 'supersymmetry'[11]. One of the main goals of the forthcoming Large Hadron Collider will be to see whether this is correct — if it is, a whole new world of phenomena will open up, involving new heavy partners for all known particles. But supersymmetry, as it solves old problems, poses new ones. Supersymmetric theories provide new mechanisms whereby protons might decay[12,13], and the predicted rates are already precariously close to violating experimental limits. More experiments could intensify the crisis — or begin to bring it to a satisfactory climax.

It might be said, with some justice, that I have erected here an enormous inverted pyramid of theory, supported on one point. But what an improvement this is, over no support at all! Suddenly, and at last, we begin to see the embodiment of long-anticipated, seductive dreams of pure reason. ☐

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SO(10) marshals the particles

By unifying quarks and leptons into a single class, the most important properties of these particles can be summarized in a set of rules for dealing with symmetrical symbols. The appropriate mathematical structure (the 16-dimensional spinor representation of SO(10)) is formidable, but some appreciation of the scheme can be conveyed fairly simply.

The core of the Standard Model is the idea that the non-gravitational interactions of matter, the strong, weak and electromagnetic interactions, are all described by the responses of particles called gauge bosons (the photon, for example) to several types of charge. These charges are usually called 'colours'. The gauge bosons of the strong interaction respond to and change three colours, usually called red, white and blue. The gauge bosons of the weak interaction respond to and change two colours, let us call them green and purple. The remaining 'hypercharge' gauge boson, from which the ordinary photon is constructed, responds to a combination of charges: one-half the sum of green and purple, minus one-third the sum of red, white and blue. The Standard Model does not explain why this particular combination is picked out, but it is inevitable within unification schemes such as SO(10).

This follows from one of the formal rules, the 'bleaching rule', that an equal mixture of all available charges cancels out. Thus, for example, a particle carrying a unit of red plus a unit of white colour charge will look the same, as far as the colour gluons of the strong interaction are concerned, as if it carried a negative unit of blue charge: the sum of red, white and blue units cancels.

The bleaching rule eliminates from the strong interaction the gauge boson that responds to the sum of red, white and blue charges, and from the weak interaction the gauge boson that responds to the sum of green and purple charges. These are bogus particles: 'gauge bogons'. Likewise, it eliminates from the unified model, which treats all five colours together, the gauge boson that couples to the sum of all five colours. However, the difference between total weak and strong colour charges is not bleached out. The gauge boson that responds to this (the difference between the strong and weak gauge bogons) is precisely the hypercharge component of the Standard Model.

Colours					*Hypercharge*	*Particle name*
R	*W*	*B*	*G*	*P*	$(-(R+W+B)/3 + (G+P)/2)$	
–	+	+	+	+	1/3	$\tilde{d}$
+	–	+	+	+	1/3	$\tilde{d}$
+	+	–	+	+	1/3	$\tilde{d}$
+	+	+	–	+	–1/2	e
+	+	+	+	–	–1/2	ν
–	–	–	+	+	1	$\tilde{e}$
–	–	+	–	+	1/6	d
–	+	–	–	+	1/6	d
+	–	–	–	+	1/6	d
–	–	+	+	–	1/6	u
–	+	–	+	–	1/6	u
+	–	–	+	–	1/6	u
–	+	+	–	–	–2/3	$\tilde{u}$
+	–	+	–	–	–2/3	$\tilde{u}$
+	+	–	–	–	–2/3	$\tilde{u}$
–	–	–	–	–	0	N

The multiplet shown here is constructed as a five-bit register, with entries + and –, subject to the rule that the total number of – signs is odd (in each case, changing all the signs gives the right-handed particle equivalent, not shown). Each entry corresponds to either plus or minus half a unit of the associated colour charge. So the first particle has half a unit each of green and purple charge; these cancel according to the bleaching rule, so this particle has no weak interaction. It has minus half a unit of red charge, and half a unit each of white and blue charge, equivalent to minus a full unit of red charge. These are precisely the properties of one of the particles in nature: the antiparticle of the right-handed red down quark. In all the rows up to the last, we find a precise match between the mathematical demands of this scheme and observed particles.

But the last row describes a totally bleached particle. It has neither strong, nor weak, nor electromagnetic interactions. It is none other than our new friend, the particle that according to this scheme gives mass to the neutrino: the N.