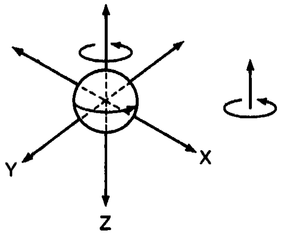
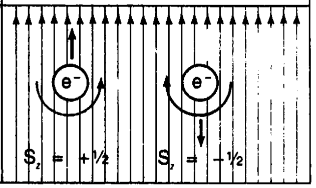
The riddle's solution lay in an old idea called *isotopic spin*. The concept of isotopic spin, although not the name, was invented by Heisenberg as an almost extraneous sidelight to his theory of the nuclear force. As a matter of convenience, Heisenberg imagined the proton and the neutron to be different states of the same particle, in somewhat the way that the atomic isobars carbon-12 and nitrogen-12 have the same mass but different charges. (By right, the name should really be "isobaric spin," not "isotopic spin," because the reigning metaphor has nothing to do with atomic isotopes, such as carbon-12 and carbon-14, which have different mass but the same charge.) To describe this relationship formally, Heisenberg proposed that each particle be thought of as spinning like a top in some imaginary space. If the axis of spin points up, the particle has a positive charge and is a proton; if the axis points down, it has no charge and is a neutron. Heisenberg said that the proton and the neutron could then be assigned the same value—½—of a hypothetical quantity later baptized isotopic spin.[122] One recalls that ordinary spin, too, is associated with a direction, and thus an electron with spin ½ has an axis of spin that is indicated by saying that its spin orientation (S_z in

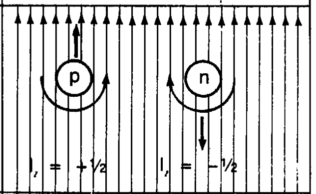
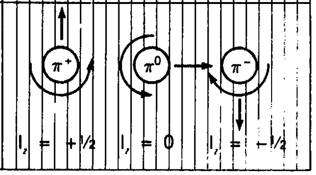
the diagram) is +½ or −½. Similarly, isotopic spin is associated with a direction, and thus the upward proton is said to have an isotopic spin orientation (I_z in the diagram) of +½; the neutron, −½.[123]

As put forth by Heisenberg, isotopic spin was not only complicated and confusing, but also of little real use; most of his colleagues paid little attention. Four years later, however, a single issue of the *Physical Review* con-



An upward axis of spin

Ordinary Spin	Particle	Orientation of Spin in Magnetic Field (technically known as S_z because it is the z axis on graph.)
S = ½	Electron	 S_z = +½ S_z = −½

Isotopic Spin	Particle	Orientation of Isotopic Spin in Imaginary Charge Space (technically known as I_z, as above)
I = ½	Nucleon	 I_z = +½ I_z = −½
I = 1	Yukawa particle, or pion	 I_z = +½ I_z = 0 I_z = −½

ORDINARY SPIN AND ISOTOPIC SPIN

tained three papers that dramatically resuscitated the idea. The first gave an experimental value for the force that clamped together protons in the nucleus; the second analyzed the data to show that the force was equal between two protons and a proton and a neutron; the third used the first two as an excuse to relaunch isotopic spin, arguing that the nuclear force, whatever it was, could not "see" the difference between the proton and neutron, and that therefore they should be regarded as two states of one particle called the *nucleon.*[124] In 1938, one of Pauli's assistants, a Russian emigré named Nicholas Kemmer, extended the idea past the nucleon. He showed that if one were to take seriously Yukawa's notion of a particle that transmitted the nuclear force, one would actually have to assume the existence of three such entities—three pions, in today's language—that could be regarded as states of one particle, with three different axes of isotopic spin: up, down, and sideways.[125] (Note that, as in the case of the pion, the isotopic spin of the particle may have a value of 1, whereas its axis of spin may be some other number, such as 0.)

In an important paper, Oppenheimer and Serber then postulated that the total amount of isotopic spin stays the same in particle interactions, in the same way that the total energy, momentum, and electric charge do not change.[126] All four are said to be "conserved." The difference is that the conservation of isotopic spin is approximate; it is conserved only in interactions involving the nuclear force, whereas energy, momentum, and electric charge are conserved no matter what.

A hitherto unknown law of nature had shown its presence, but briefly, like a flash at the corner of an eye. Enter Abraham Pais, vigorously. Pais was a Dutchman then at the Institute for Advanced Study. In a remarkable talk at a 1953 conference commemorating the hundredth birthday of Hendrik Lorentz, Pais indicated the course that elementary particle physics would follow for the next two decades.[127] Pais was thirty-five; much of his twenties, ordinarily among the most productive years of a physicist's life, had been spent hiding from the Germans in Amsterdam. Eventually he was caught and put into a Gestapo prison. He was lucky enough to survive. Earlier than most Occidental theorists, he had the hunch that the new cosmic ray particles were important.[128] In the years before the Lorentz conference, Pais and several Japanese had come independently to a conclusion that now seems baldly obvious: The creation and decay of V particles are not attributable to the same agent. Unable to think of a real reason why this should occur, Pais complained about the lack of clues: "The search for ordering principles may indeed ultimately have to be likened to a chemist's attempts to build up the periodic system if he were given only a dozen odd elements."[129] Speaking at the Lorentz conference, he began by listing "a number of questions in meson physics that seem to be of outstanding interest."

> *The first question concerns the isotopic spin. Ever since it became clear that proton and neutron can transform into each other and in many instances are exchangeable in nuclear systems, we have been faced with the question whether a theoretical foundation could be given for the fact that these two particles seem to behave like different states of one entity now called [the] nucleon. The formal shorthand of isotopic spin takes cognizance of the situation but explains nothing of course.*[130]

He then argued, in general and by example, that great discoveries were yet to be made, for new variables like isotopic spin would be the key to the study of both the nuclear forces and the cosmic ray particles. More such intrinsically conserved qualities should be sought, and their description merited the introduction of new quantum numbers, the first in twenty-five years. (Using today's language, Pais was the first to urge the search for higher symmetries.) By pushing and pulling these properties, twisting them into mathematical knots, one could rank the elementary particle interactions into a hierarchy and peer inside their inner workings.

Although encumbered by a half-dozen other ideas and a wholly incorrect model, a program for the next generation lies swaddled within the nervous evidence of Pais's creativity. The paper had little direct influence, however, because it was almost immediately superseded by a concrete example of the kind of inquiry Pais advocated, in the form of a new quantum number proposed by a twenty-two-year-old named Murray Gell-Mann, who was then beginning a meteoric ascent into prominence. A young man who gave a rich new layer of meaning to the term "brash," Gell-Mann knew almost nothing about Pais's ideas; he had been led to the same considerations independently.[131] Whereas Pais's style was more discursive and conversational, Gell-Mann was terse, oblique, clipped. One article was a hint, the other an announcement: Another era had begun.

Gell-Mann's paper—"Isotopic Spin and New Unstable Particles"—is remarkable, a pocket symphony in the modern style. It begins with a quick fanfare:

> *[L]et us suppose that both "ordinary particles" (nucleons and pions) and "new unstable particles"* [here a list of V particles] *have interactions of three kinds:*
> (i) *Interactions that rigorously conserve isotopic spin. (We assume these to be strong.)*
> (ii) *Electromagnetic interactions. (Let us include mass-difference effects in this category.)*
> (iii) *Other charge-dependent interactions, which we take to be very weak.*

This music, familiar to the cognoscenti, had never sounded so clearly. In modern terms, one speaks of a hierarchy of interactions: *electromagnetism,* which binds the electrons around the nucleus, conserves electric charge, and is fully described by a field theory, quantum electrodynamics; the *strong force,* which holds the nucleus together, conserves isotopic spin, was thought to be transmitted by pions, and had no theory to describe it whatsoever; the *weak force*, which causes particles to decay into lighter particles, does not seem to conserve anything at all, was not known to be transmitted by any particle, and was imperfectly covered by Enrico Fermi's theory of beta decay; and *gravity*, which holds planets around suns and suns in galaxies, is fully described by the theory of general relativity, plays no role on the subatomic level, and until recently seemed unreconcilable with quantum mechanics. Today, electromagnetism, the strong and weak interactions, and gravity are thought to be the basic forces of the Universe, from which all others derive.

This ordering of forces was matched at about the same time by an ordering of the particles they affected. Particles that feel the effects of the strong force are now known as *hadrons*. Hadrons in turn are split into two subcategories, the heavy *baryons*, like the proton and neutron, and the lighter *mesons*, like the pion. Those particles, such as the neutrino and electron, which do not feel the effects of the strong force, are called *leptons*.[132] Four interactions for leptons and hadrons: the cosmos in a clause.