FEATURE

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Research Area: Experimental Physics

Grand Unification and the Search for Proton Decay

Proton Decay Search Tests Grand Unified Theories

One of the long standing goals of physicists is the unification of the forces of nature by using a single mathematical description. The electromagnetic and weak forces already have a single description (the electroweak theory) and the next step is the inclusion of the strong force. The various attempts at this unification are called GUT's (Grand Unified Theories). The energy at which this unification occurs is unknown, but is expected to be at about 10^{16}GeV. Exploration of this energy scale is a challenge since this energy is far beyond that which we could explore with accelerators. However, in most grand unified theories, the proton is predicted to decay. The observation of the decay and the study of the particles that it decays into could establish grand unification and distinguish between models. Thus, the search for proton decay provides one of the few approaches to the problem of confronting grand unified theories with experimental data and any progress toward this goal has unique value for the future development of physics.

The early searches for the decay of the proton were motivated by the testing of conservation laws. In physics, conservation laws are powerful tools which allow us to understand the behavior of matter. Some of these laws, such as conservation of energy, conservation of linear and angular momentum, conservation of charge and others, are familiar from classical physics and are exact and based on general theoretical principles. Others, are purely empirical, in other words, they have no obvious theoretical justification and are proposed to account for the experimentally observed absence of some reactions. This second group includes the conservation of baryon number, the conservation of lepton number and others. In general, we expect any reaction not forbidden by a conservation law to occur, although perhaps not very often. The exact conservation laws correspond to symmetries in nature. For example, the conservation of momentum and angular momentum

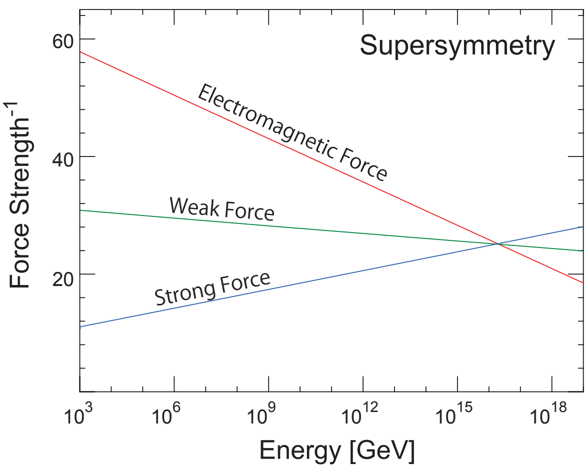

Figure 1. The unification of forces

can be traced to translational and rotational symmetry.

The absolute stability of the proton was first suggested by Weyl in 1929. In 1954, Goldhaber, arguing on very general grounds showed that the lifetime of the proton had to be greater than 10^{18} years and also in 1954, the first experimental limit on the lifetime of the proton, greater than 10^{20} years, was obtained. From 1954 to 1974, these limits were gradually improved by making use of larger and larger detectors which were built for other purposes. In 1974 the situation changed. The first promising grand unified theory, SU(5), was published which predicted the lifetime of the proton to be between 10^{27} and 10^{31} years, comfortably above the latest lifetime limit, but within reach of a dedicated experiment.

Gigantic Detectors Required for Proton Decay Search

While the community now had a predicted lifetime to test, the scale of the required experiment presented a challenge. Proton decay is a statistical process. If you watch a single proton you would have to wait 10^{31} years to see it decay. On the other hand, if you have a container with 10^{31} protons in it, on the average, one proton will decay per year. There are about 6×10^{29} protons (and neutrons) in a ton of material so the required detector size is 100 ton-scale. To be conservative, a kiloton scale detector would be necessary. The first of these detectors, IMB in the U.S. and Kamiokande in Japan, turned on and gave results in the 1980's. Unfortunately, they did not observe the predicted decay rate and thus set lower limits on the proton lifetime that were higher than that predicted by SU(5). In this way, the first of the grand unified theories fell victim to experiment.

Since the time of IMB and Kamiokande, a wide variety of alternative grand unified theories have been developed. These include the assumption that the fundamental mathematical symmetry is larger than SU(5) and the possibility of supersymmetry. Some attractive models stress the connection between neutrino masses, mixing and proton decay. In general they predict new modes of decay and longer lifetimes.

Thus, continued progress in the search for proton decay inevitably requires larger detectors. Since the lifetime of the proton is unknown, *a priori*, and could range from just above present limits to many orders of magnitude greater, increases in sensitivity by factors of a few are insufficient to motivate new experiments. An order of magnitude improvement can only be achieved by running Super-Kamiokande for many, many more years, or by constructing an order of magnitude larger experiment.

Super-Kamiokande Holds the Current World Records

The "classical" proton decay mode, $p \to e^+\pi^0$, can be efficiently detected with low background. At present, the best limit on this mode ($\tau/\beta > 8\times10^{33}$ yr, 90% CL) comes from Super-Kamiokande. Supersymmetric theories favor the mode $p \to \nu K^+$, which is experimentally more difficult due to the unobservable neutrino. The present limit from Super-Kamiokande is $\tau/\beta > 2\times10^{33}$ yr (90% CL). However, the actual decay modes of the proton are also unknown, *a priori*, and can produce quite different experimental signatures, so future detectors must be sensitive to most or all of the kinematically allowed channels. Moreover, the enormous mass and exposure required to improve significantly on existing limits (and the uncertain prospects for positive detection) underline the importance of any future experiment's ability to address other important physics questions while waiting for the proton to decay. Proton decay experiments have made fundamental contributions to neutrino physics and particle astrophysics in the past, and any future experiment must be prepared to do the same.

A variety of technologies for discovery of proton decay have been discussed. Of these, water Cherenkov appears to be the only one capable of reaching lifetimes of 10^{35} years or greater. Other techniques, for instance liquid Argon or liquid scintillation, have been discussed but their putative advantages are largely speculative and the feasibility of their employment on the scales required is far from proven.

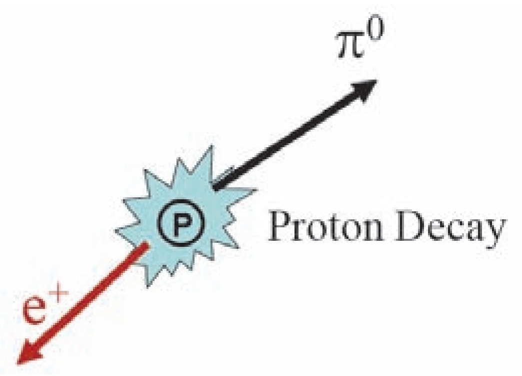

Figure 2. A schematic of the proton decay mode $p \to e^+ + \pi^0$

Global Efforts toward Next-Generation Experiments

In order to carry the search forward it will require a renewed commitment to this essential physics, ideally as part of a global effort. Research groups in Europe, Japan and the United States are fully cognizant of the need to work together (and indeed are already doing so). Cooperative, parallel studies of future underground water Cherenkov proton decay experiments are underway in the U.S. (at the new DUSEL site), Japan (Hyper-Kamiokande) and in Europe (MEMPHYS). The proposed designs are at the megaton scale. Detailed Monte Carlo studies, including full reconstruction of

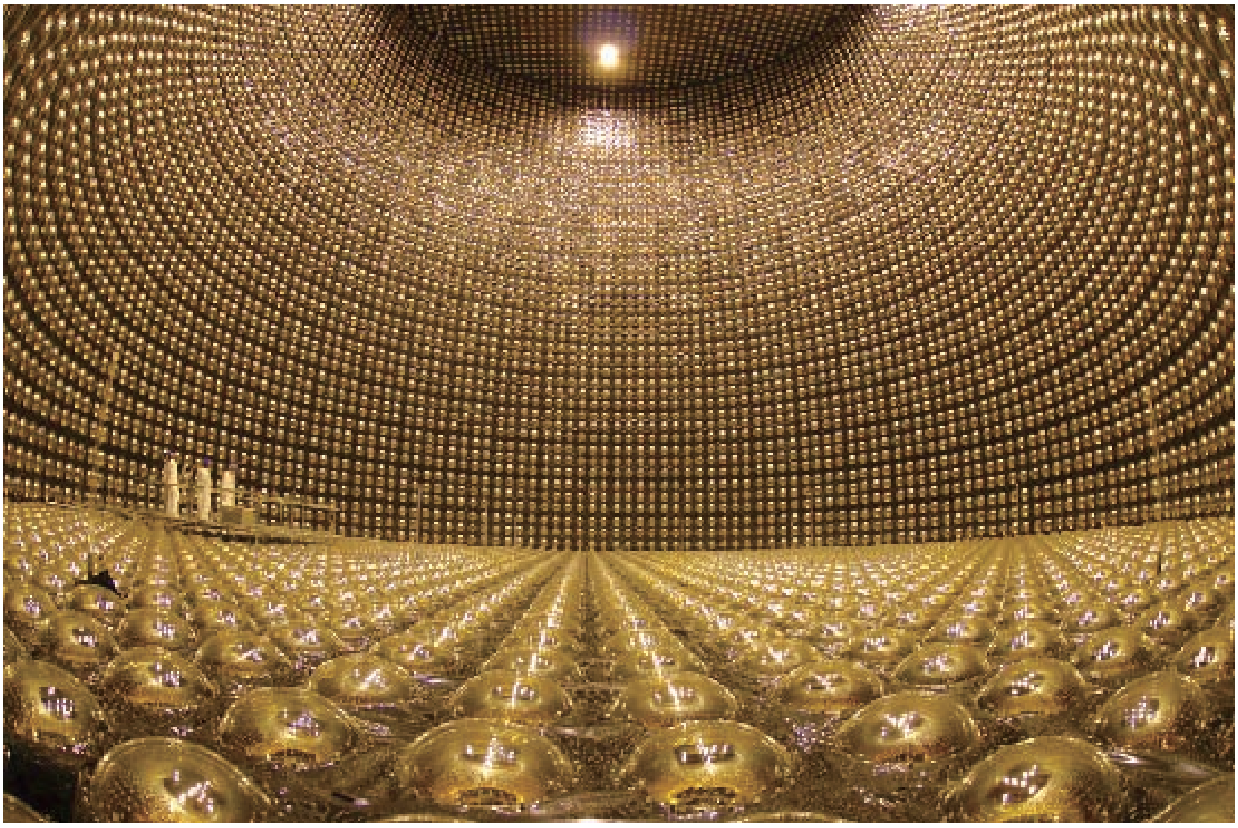

Figure 3. The Super-Kamiokande detector after replacing damaged tubes and before filling with water.

simulated data, indicate that the proposed detectors could reach the goal of an order of magnitude improvement on anticipated proton decay limits from Super-Kamiokande. With sufficient exposure, clear discovery of proton decay would be possible even at lifetimes of (few) × 10^{35} years. A detector with mass O (1 Mton) would also be a powerful tool for studying neutrino physics.

Super-Kamiokande continues to produce superb and exciting results. There is every reason to expect that the next generation proton decay experiment will accumulate an equally impressive list of accomplishments, if support commensurate with its physics potential is forthcoming.

R&D towards more efficient and economical photo-detection – both improved conventional photo-multiplier tubes and more novel technologies – while not required to build the next large detector, could reduce its cost and increase its physics reach considerably. This R&D should be strongly supported, since they will also benefit a host of other research efforts.

Finally, the search for proton decay is only one of many particle physics and astrophysics activities requiring extensive, modern underground infrastructure. A national underground laboratory being planned in the U.S. would greatly facilitate not only proton decay, but a whole spectrum of large and small experiments now being planned or discussed. Such a laboratory would undoubtedly achieve tremendous economies, by providing a single, centralized infrastructure for many experiments, each of which would otherwise be forced to duplicate it themselves.