Symmetries provide us with insights into fundamental principles of nature. A symmetry in subatomic physics is a similarity that exists when some natural phenomenon is looked at from a different point of view, in a mirror rather than directly, for example. The similarity often points to a deeper understanding of the intrinsic properties of subatomic particles and their interactions. Symmetries predict the way these particles interact with each other, and so can be tested with high precision in experiments at accelerators such as the ones at TRIUMF.

The TRIUMF Weak Interaction Symmetry Test (TWIST) is an example of such an experiment. It is designed to measure accurately the distributions in energy and angle of positrons ($e^+$, the positively charged antimatter twin of the electron) produced when heavier positive particles called muons ($\mu^+$, named for the Greek letter, mu) disintegrate. Like electrons, muons can be either negatively or positively charged. They are produced in great numbers when the TRIUMF proton beam strikes a target of graphite or beryllium. Muons live only about two millionths of a second on average before disappearing or decaying. When a muon decays, it produces two neutral, almost massless particles called neutrinos, as well as an electron or positron depending on the charge of the original muon, in order that electric charge be conserved. This decay is an example of what physicists call the “weak interaction”, which is also responsible for a type of radioactivity known as beta decay. Along with the very closely related “electromagnetic interaction”, responsible for gamma radioactivity, it can be calculated very precisely using only a few measured parameters as input. This is in contrast to the more complicated “strong interaction”, describing alpha radioactivity and other processes involving nuclei and their constituents.

Unlike beta decay, muon decay does not involve any strongly interacting particles. It is one of very few weak interactions that is free of the potentially more complicated effects of strong interactions. The muon is a very interesting particle in other respects, too. While its ultimate raison d’être is not clear, it does fit neatly into the scheme of fundamental subatomic particles which includes all known weakly interacting leptons and strongly interacting quarks. The graphic shows the muon in its place within the second of three known generations of leptons and quarks. First generation particles make up all of the matter of our everyday world, while the muon is the lightest, most easily studied particle in the second. There is the hope that detailed study of muons will help us understand why the second and third generations exist, an important question whose answer still eludes us. The muon has some other advantageous characteristics. It has the property of intrinsic angular momentum called spin, which results in the muon having an orientation or direction in space. Our understanding of the weak interaction to date is very much dependent on characteristics related to spin.

A very general space-time symmetry predicts the distribution in angle and energy of the positrons produced when muons decay, where the positron angle is measured with respect to the direction of the muon spin. The prediction is made in terms of the symmetry of the interaction itself, plus the space and spin characteristics of the particles taking part, the muon, positron, and the two neutrinos. So far, of those possibilities allowed by this quite general symmetry, only a very limited type has been observed; this limitation is considered to be evidence of a more specific, restrictive symmetry. But what is it and why is it so restrictive?
To explain this and other observations, physicists use what has come to be known as the Standard Model. While it has been very successful and has survived many tests since it was devised about forty years ago, it is considered to be only an approximation to a more complete and correct explanation. Many parameters of the model, such as the masses of the fundamental particles, are not predicted but rather have to be inserted to match observation. To help us to decide which of the many possible alternatives are closest to what nature really looks like, we search for examples in which the model might fail. By finding failures we narrow down the options for the correct theory. Much of the research in subatomic physics today is aimed at finding the limitations of the Standard Model, searching at the extremes of our knowledge for some place where it might not be valid. The TWIST experiment is one of these tests, accurately measuring muon decay, looking for symmetry properties not contained in the Standard Model but which would be perfectly compatible with a more general symmetry.

We can plot the Standard Model prediction of the distribution in energy and angle of positrons from muon decay, as shown in the figure. The energy is shown in terms of a number $x$, ranging from near zero up to its maximum of one. The angle $\varphi$, between the positron direction and the muon spin direction is plotted in terms of a function $\cos(\theta)$, which is convenient because it produces a flat line if positron emission is equally likely in all directions. As you can see, the Standard Model prediction is by no means flat in either $x$ or $\cos(\theta)$, due to the specific symmetry it assumes.

From previous experiments, we know that this distribution is correct to an accuracy of a few parts per thousand. The goal of TWIST is to increase the accuracy to a few tenths of parts per thousand, to search for a possible failure of the Standard Model and a hint at what might be beyond. While this is technically very challenging, it is well matched to the abilities of TRIUMF and its facilities, where precisely defined high-intensity beams of muons can be produced and high-precision detection systems to measure the decay can be designed and built.

The cyclotron at TRIUMF provides a source of very highly polarized (spin-aligned) low-energy muons, called “surface muons” because they originate at the surface of the target struck by the cyclotron’s proton beam. These muons are guided by a beam line toward a high-purity spin-preserving material surrounded by an array of precision detectors. The muons slow down and come to rest at the very centre of the detector array which measures the energy and direction of emission of the positrons produced in the decay of the muons. The angle $\theta$ mentioned above can also be determined since the distribution of spin direction of all the muons is known. As shown in the artist’s depiction of the TWIST spectrometer, the set of detectors is inside a high magnetic field of two Tesla, or about fifty thousand times the strength of the earth’s magnetic field, produced by a large superconducting magnet originally built for the medical diagnostic application of Magnetic Resonance Imaging (MRI).

The array of detectors is shown in the photo (see next page), arranged in its cradle prior to installation in the magnet. Comprised of about five thousand wires, each with a hair-like diameter of fifteen thousandths of a millimeter and located to a precision of a few thousandths of a millimeter, the array is able to locate the position of the positron from muon decay at many points along its track in the magnetic field. This is accomplished by electronically measuring and recording several thousand bytes of information.
for each muon decay. From the path of the track and its curvature in the magnetic field, the initial direction or angle, and the energy of the positron can be deduced. Each second, the data from decays of several thousand muons are recorded; in an hour the equivalent of about thirty audio CDs of information is stored for later analysis.

Based on the measured track coordinates from each of these millions of decays, a computer must analyze and calculate each positron’s energy and initial angle. This massive task can be accomplished only with a very powerful computing installation. For this, TWIST relies on the WestGrid distributed computing environment recently installed at UBC. Analyzing data tracks is only part of the task for these processors; it is also necessary to carry out detailed simulations of the decays as they would be seen in the TWIST spectrometer, assuming that the Standard Model is valid, and to analyze the simulated data in exactly the same way as the real data. After careful verification of the simulation’s validity, the results are compared with experimental data in a way that is “blind”, that is, the scientists cannot anticipate whether the comparison does or does not support the Standard Model until the final step.

The huge amount of data recorded by TWIST is necessary to achieve our goal of a high accuracy measurement of muon decay. In the first place it is important to reduce what are known as statistical uncertainties arising from statistical fluctuations in numbers of events of any particular characteristic. All measurements which count numbers, for example consumer or political opinion polls, must assess these kinds of uncertainties, and there are well accepted methods to do so. There exists another class of uncertainties, called systematic uncertainties,
which are more challenging for this experiment. They result from, for example, incorrect calibrations or uncontrollable changes in experimental conditions. With its high data rate, TWIST can achieve adequately small statistical uncertainties. However, systematic uncertainties pose a set of quite different problems requiring individual solutions. They will eventually set the limit to the precision of the result which can be achieved.

Evaluating and reducing systematic uncertainties is made easier with the availability of large amounts of data. For example, the effect of a variation in the muon beam position on each parameter describing muon decay can be deduced by actually changing the muon beam position and repeating the measurement. Often, the change can be exaggerated by different amounts. Then, by controlling the position of the beam very carefully, and by assessing how much movement might still be present in the real beam, it is possible to estimate the amount by which the decay parameter could be affected. Not only can this be accomplished with experimental data, but the use of large sets of simulated data is also essential. Variations are introduced into the simulation which correspond to real changes in the experiment. After verifying that the changes in simulated data are consistent with corresponding real data sets, the simulation can be used for more extensive studies of systematic errors and uncertainties.

Many other possible uncertainties exist. They range from specific detector characteristics such as position calibration and resolution to atmospheric density which affects detector response as well as the spatial distribution of muons at the time of decay. Where possible, variables contributing to systematic errors are controlled to the degree required to make the errors insignificant; otherwise, the contributing variables are monitored with a precision that allows the estimation of their effect on the measurement.

The substantial analysis tasks required are well underway. The TWIST collaboration consists of about 40 scientists, engineers and technicians who come from TRIUMF and the Universities of Alberta, British Columbia, Montréal and Regina in Canada, Texas A&M and Valparaiso in the United States, and the Kurchatov Institute in Russia. The group includes five graduate students and three postdoctoral research associates.

The first results from TWIST are expected in late 2004. They will improve upon previous measurements, but the eventual goals of the project will be accomplished only after several more years of data taking and detailed analysis. Will the symmetry of the Standard Model survive in muon decay, or will there be some feature of the more general symmetry that is revealed?

Follow the future of TWIST at http://twist.triumf.ca

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