TITAN

Jens Dilling

Nuclear and particle physicists study matter at the very smallest scale, exploring the structure and interactions of the most fundamental particles that make up everything in the universe, from stars to starfish. Over the past few decades many experiments have confirmed the picture of all matter as being made up of quarks and leptons. The coupling of these particles is described by the Standard Model of fundamental particles and interactions, which accounts remarkably well for the world we live in. Thus, it explains the forces that hold both atoms and nuclei together.

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However, the Standard Model leaves many important questions unanswered. Why do three families of quarks and leptons exist? Can we understand the source and pattern of their masses? Will we discover more types of particles and forces at yet higher-energy accelerators? Are quarks and leptons really fundamental, or do they, too, have substructure? What is the nature of dark matter? Questions such as these provide the stimulus for ongoing research in nuclear and particle physics. At TRIUMF a large amount of this research is now centered at ISAC.

ISAC is one of the leading facilities world-wide for the production of exotic nuclei. Exotic or radioactive nuclei are made up of protons and neutrons, just as their stable brothers, but have an unbalanced ratio of these. As a result, they undergo radioactive decay in order to change this ratio to a more stable configuration. The decay that transforms a neutron into a proton or a proton into a neutron is called beta-decay. At the quark level, the proton consists of 2 *up* quarks and a *down* quark while the neutron consists of an *up* quark and 2 *down* quarks. In order for a proton to convert into a neutron one of its *up* quarks must change into a *down* quark. This change is brought about by the weak force. In addition to the quark transformation, the positive charge carried by the proton must be removed, since the neutron is electrically neutral. This is done by emitting a positively charged beta-particle, which gives this form of transformation its name: beta-decay. Similarly for the conversion of a neutron, consisting of 2 *down* quarks and an *up* one, into a proton, one of its *down* quarks must change into an *up* quark and a negative beta-particle is emitted.

An important problem we want to address at ISAC is whether the Standard Model is complete with only three families of quarks and leptons. We attack this problem through the observation of the beta-decay of exotic nuclei containing an excess of neutrons. The measurable quantities are the half-life of the radioactive nuclei and the energy available for their decay. A simple relationship between these quantities which should be the same for all nuclei is predicted by the Standard Model since, in each case, we have the same change between *up* and *down* quarks. However, depending on the particular nucleus undergoing decay there will be different environments of other protons and neutrons, which lead to small corrections to the relationship predicted by the Standard Model. At present there appear to be slight discrepancies between the data and model predictions, but these might be accounted for by inadequacies in the calculation of the theoretical corrections. Measurements with **TITAN** (**T**RIUMF's **I**on **T**rap facility for **A**tomic and **N**uclear science) will provide more precise experimental data, which will check this possibility.

Precision half-life measurements are already under way at ISAC and some results have been reported. The other experimental quantity, the available decay energy, can be determined from a precise measurement of the masses of the initial and final nuclei involved in the decay. The available decay energy, E, is then given by Einstein's mass-energy relationship, $E=\Delta m\ c^2$, where Δm is the mass difference between the two nuclei, before and after the decay.

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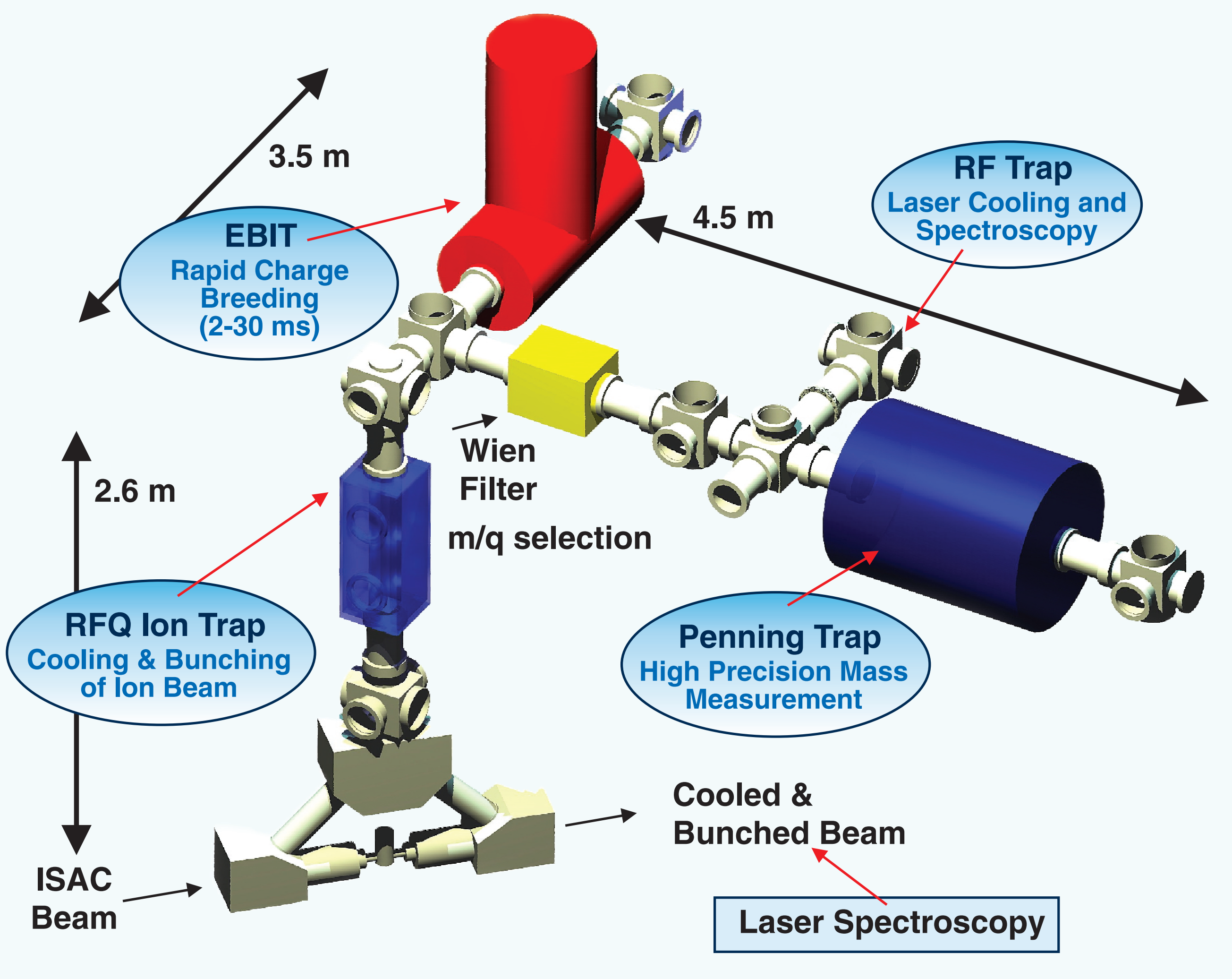
TITAN's task at ISAC is to measure very precisely the masses of short-lived exotic nuclei, which will provide information necessary to allow calculation of the detailed corrections needed for a critical test of the Standard Model. The precision needed in the mass measurement is about one part in 100,000,000 corresponding to determining the mass of a car with a precision of about 10 milligrams.The fact that the nuclei of interest have an average half-life of only about one-tenth of a second makes this an extremely difficult task. The TITAN approach to the problem involves two important features: an extremely well-controlled environment, and a measurement of frequency as the primary mass-related experimental observable.

The environment is generated by a Penning ion trap. Such a trap uses a combination of magnetic and electric fields to provide a region in space where ions are trapped. Since this region is at an extremely low pressure the ions do not interact with any material. The magnetic and electric fields are shaped with a precision that makes it possible to understand the motion of the ion extremely well,

TITAN: TRIUMF's Ion Trap for Atomic and Nuclear Science



The proposed TITAN facility at TRIUMF/ISAC; located 2.6 m above the present beam line level. The multi-component system will allow for a wide variety of fundamental and applied physics experiments.

and allows control, once the ion is trapped, with almost arbitrary accuracy. At CERN, for example, single anti-protons (stable, non-radioactive anti-matter) could be trapped and kept from interacting and annihilating with normal matter for several months at a time. The pressure, hence, the number of residual gas-atoms or molecules per cubic millimeter, in the trap was less than in outer space between stars.

“The precision needed in the mass measurement is about one part in 100,000,000, corresponding to determining the mass of a car with a precision of about 10 milligrams in one tenth of a second.”

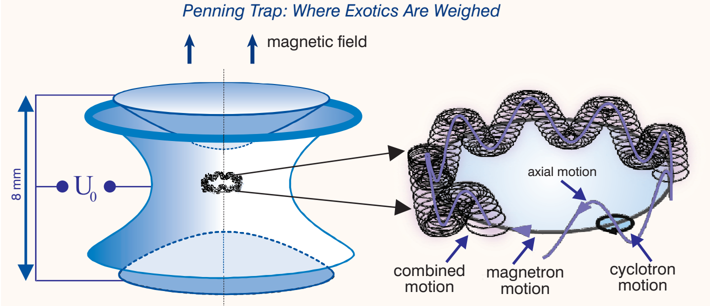
If an alternating electric field is applied to the static electric and magnetic fields used to confine the ions in the Penning trap, the ions can be made to act as though they were in a (very!) small cyclotron. The exact frequency at which this happens is inversely related to the mass of ion. Thus the mass measurement is changed to a frequency measurement. (Of all physical quantities frequency measurements are capable of the highest precision.) Besides the measurement of this frequency, one needs to know the charge state of the ions and the magnetic field strength, both of which are straightforward measurements. Once the mass is measured the available energy for the beta-decay process can be determined.

Before entering the TITAN Penning Trap, the exotic nuclei, which come from the ISAC facility in the form of an ion beam, need to undergo a series of preparatory steps as illustrated in the figure on the previous page. The first step takes place in an **RFQ** (**R**adio-**F**requency **Q**uadrupole) ion trap. This trap consists of four rods to which an alternating high-frequency voltage is applied. By proper choice of the frequency and the voltage, the ions can be confined between the rods, being alternately attracted and repelled by, but never touching, the rods. In addition the device is filled with a cold gas and the interactions with it leads to a cooling of the ions. This device accomplishes two things: a large number of ions is accumulated and their energy (temperature) is reduced to a value better suited for our precision mass measurements.

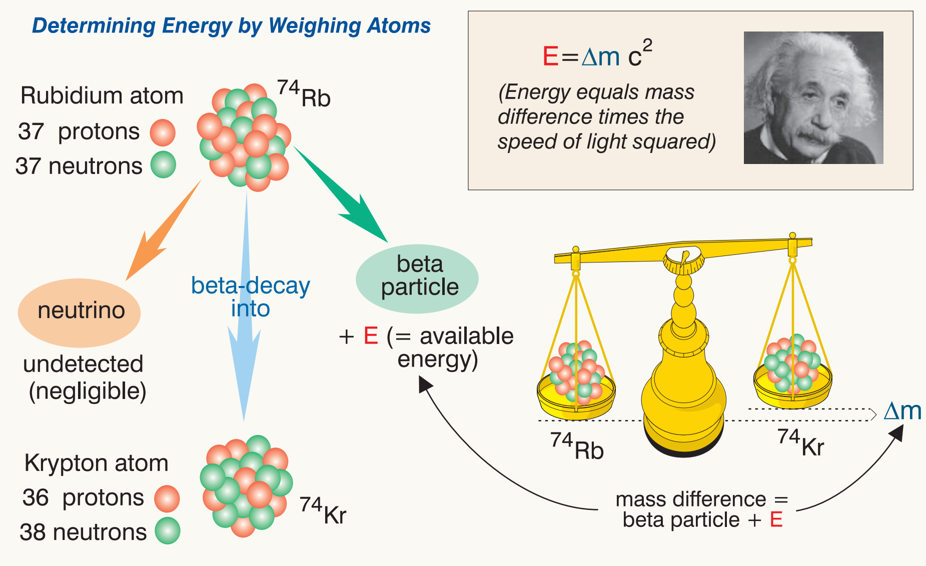
The next step in the TITAN system is an **E**lectron **B**eam **I**on **T**rap (EBIT). The purpose of this device is to reach higher charge states, by removing more and more electrons from the atom or ion. This is done by bombarding the trapped particles with an electron beam, which collides with the electrons of the atoms, and kicks them out. This process works, as long as the binding energy of the electron (a measure of how tightly the electron is attached to the nucleus) is smaller than the energy of the incoming beam. The process is a dynamic rather than a well controlled one, since the kicked out electrons may attach to other ions. As a result the ions that are extracted from this trap are a cocktail of ions in various charge states.

The Penning trap mass measurement requires, however, the exact knowledge of the charge state of the trapped ion. In the next step, a Wien filter, the ions travel through a region in which electric and magnetic fields are at right angles to one another and the direction of the incident ions. With such a configuration only ions of one specified charge

Penning Trap: Where Exotics Are Weighed



Schematic Penning trap with magnetic field pointing upwards, and motion of stored ions there in. The complicated combined motion of the ions is composed of the axial, the slow magnetron, and the fast cyclotron motion. The total behavior of the ions has been investigated and is now understood extremely well.



Schematic beta-decay of a radioactive Rubidium atom (composed of 37 protons + 37 neutrons = 74 nucleons, therefore called ^{74}Rb) into a Krypton atom (36 protons + 38 neutrons = 74 nucleons, called ^{74}Kr). By weighing the two different atoms, the available energy, E, for the beta-decay is determined.

will be able to go straight through and into the Penning trap.

The need for high charge states comes from the requirement to perform the Penning trap mass measurement quickly, since the nuclei of interest are radioactive and decay. In the quantum world there are pairs of variables both of which cannot be simultaneously measured to high accuracy. This is Heisenberg's uncertainty principle which says, for example, that the better the position of a particle is determined, the less precise its momentum is known. Another pair of such variables is energy and time. Longer observation times lead to higher precision mass (energy) measurements. The radioactive ions in the Penning trap, however, only allow a short observation time before they decay.

The way out of this apparent dilemma, is to use highly charges ions because the frequency at which they absorb energy is directly related to their charge. Note that time and frequency measurements are very closely related. Since we are stuck with a frequency uncertainty due to Heisenberg's principle, we still can reach a better value for the relative precision of our measurement by boosting the absolute value of the frequency. This is done by using highly charged ions. By comparing the frequency so measured to that for a trapped stable ion, whose measurement can take place over a much longer time, we reach the necessary absolute precision for mass measurements of exotic nuclei.

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TITAN is the first system that will use this combination of various ion traps and techniques. It will provide the crucial data required to evaluate the validity of the theoretical corrections needed for a test of the Standard Model. The uniqueness of the system allows for other fundamentally important experiments in the fields of, for example, atomic physics, where laser spectroscopy measurements are foreseen.

The TITAN system was proposed to NSERC and has received funding to be built over the next three years. The main investigators are based at TRIUMF and eight other Canadian universities, but the collaboration is truly international, with parts of TITAN (the EBIT) being built at the Max-Planck Institute for Nuclear Physics in Heidelberg, Germany. Precision mass measurements are planned to begin in 2006.

Jens Dilling is a research scientist at TRIUMF and leader of the TITAN Ion Trap Group.