Beta decay: A window on fundamental symmetries

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Beta rays were first identified by Rutherford in the last decade of the Victorian era, well before atoms were even suspected of containing nuclei, or that their nuclei would give us access to still smaller particles and yet more fundamental interactions. These beta rays were soon demonstrated to be electrons, but the natural radioactive process that produced them, nuclear beta decay, presented scientists with a sequence of puzzles, which took more than half a century to solve, and led to the discovery of a new particle, the neutrino, as well as the identification and characterization of a new force. This "weak" force turned out to have truly astonishing properties, including among them the violation of several long cherished symmetries. Now, after nearly 120 years, "beta rays" continue to be studied with ever greater precision, and the information they yield on fundamental symmetries remains at the forefront of physics.

Nearly four decades ago, nuclear beta decay was securely placed within the framework of the new electroweak Standard Model, which successfully accounted for all the puzzles and weak-force idiosyncrasies that had arisen experimentally by that time. Since then, beta-decay experiments have turned to precision tests aimed at probing for possible limitations to the Standard Model and its embedded symmetries. Remarkably the Model has withstood these tests – and many others – without a blemish, so the important outcome of beta-decay experiments has been to solidify the Standard Model and to help reduce the scope for so-called "new physics" beyond it.

As a precision tool for probing the underlying weak-interaction physics, nuclear beta decay has both advantages and disadvantages. Among its greatest advantages is the variety of different transitions it offers: The nuclear states that serve as parents and daughters of beta transitions come in the full range of spin-parities and configurations. If some aspect of the weak interaction can be singled out by use of a specific set of parent and daughter quantum numbers, the chances are that a beta transition can be found that has exactly those parameters. Better yet, there are likely several such beta transitions, so the results from one can be checked for consistency with those from another.

Experimentally, there are advantages too. The parent states of many nuclear beta transitions can be prepared in a very favorable format, having been produced prolifically with an accelerator and been subsequently purged of contaminants. If required, they may also be polarized. Furthermore, most beta transitions are followed promptly by a second decay process, with the emission for example of gamma rays, protons, neutrons or alpha particles. This offers further flexibility, allowing angular correlations to be reliably measured, even those involving an undetected neutrino.

The main disadvantage of using nuclear decay in probing the weak interaction is that nuclear states inevitably have complicated hadronic configurations. The careful selection of a beta transition so as to take advantage of specific parent/daughter spins and parities, can still be undone by large uncertainties in the nuclear state configurations, which ultimately may dominate the results. One of the greatest challenges in designing a good measurement is to choose cases where the nuclear structure is simple and well known, or where for some reason it has very little impact on the weak-interaction parameters being studied.

My plan for these lectures is to begin by outlining a variety of ways in which nuclear beta decay can be used to probe fundamental symmetries via tests of the Standard Model and its assumptions. Some recent results will be used to illustrate current experimental capabilities and to show the extent to which these results have tested the assumptions of the Standard Model. After this general overview, I will focus on a particular case study: superallowed $0^+ \rightarrow 0^+$ nuclear beta decay between T=1 analog states.

The measured strength of a beta transition is expressed in terms of an "*ft* value", where *f* is the "statistical rate function", a phase-space integral which depends strongly on the total measured decay energy; and *t* is the partial half-life, which depends on two other measured quantities, the total half-life of the parent and the branching ratio for the superallowed transition. For superallowed $0^+ \rightarrow 0^+$ transitions between $T = 1$ analogue states, the measured *ft* value is inversely proportional to the square of the strength of an important component of the weak interaction: the vector current. One of the primary assumptions of the Standard Model is the Conservation of the Vector Current (CVC) so if one precisely measures the *ft* values for a number of superallowed $0^+ \rightarrow 0^+$ decays one can test whether that assumption is correct: Are the measured *ft* values all the same? If they are the same, their common value then establishes the value of the coupling constant, G_V, for the vector current now demonstrated to be conserved. That result opens up a still more interesting test.

Central to the Standard Model is the Cabibbo-Kobayashi-Maskawa (CKM) matrix, a unitary 3X3 matrix that relates the weak- to the mass-eigenstates of the three generations of quarks. The Standard Model itself does not prescribe the values of the individual matrix elements – they must each be determined experimentally – but does insist that the full matrix must satisfy all conditions of unitarity. Thus, any conclusive experimental demonstration that the unitarity conditions are not met would prove the need for "new physics" extending beyond the current Standard Model. Conversely, if experiment were instead to confirm unitarity, this result would circumscribe the scope of any possible new physics to an extent limited only by the quoted experimental uncertainties on the unitarity sum. Either way, there is compelling motivation here for precision measurements of the CKM matrix elements aimed at the most demanding tests possible of the matrix's unitarity. The experimentally determined value of G_V from the superallowed decays leads directly to a value for V_{ud}, the largest and most critical element of the CKM matrix and the key to testing the matrix's unitarity.

For the unitarity test to be meaningful, however, great precision is required from both experiment and theory. Since each *ft* value incorporates the results from three separate measurements – of Q_{EC}-value, half-life and branching ratio – each of those measurements demands the highest possible precision, and certainly better than ±0.1%. Great care also has to be taken in making the small theoretical corrections required to take account of the effects of the nuclear configurations.

In my lectures I will describe in some detail what is required in making precision measurements. Unlike most modern nuclear experiments, they call for simple counting equipment and sufficient experimental time to allow all the potential pitfalls of the measurement to be explored fully. This is just the opposite of what most young nuclear physicists have been exposed to in their careers so far.

I will then describe how the effects of nuclear structure can be incorporated into the analysis of these superallowed $0^+ \rightarrow 0^+$ decays. By their nature, such transitions between analog states are relatively insensitive to the nuclear structure of the parent and daughter states; nevertheless, at the level of precision that experiment has now reached, these corrections must be calculated and independently tested against unrelated nuclear data.

Finally, we will explore together what these results have so far achieved and what important conclusions can be drawn from them.

Suggested reading:

1) For an overview of Standard Model tests from beta decay – N. Severijns, M. Beck and O. Naviliat-Cuncic, Reviews of Modern Physics **78** (2006) 991.

2) For a review/survey of superallowed beta decay – J.C. Hardy and I.S. Towner, Physical Review C **79** (2009) 055502.

3) For a description of the evaluation of V_{ud} and its impact on the unitarity of the CKM matrix – I.S. Towner and J.C. Hardy, Reports on Progress in Physics **73** (2010) 046301.