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Testing the weak interaction using St. Benedict at the University of Notre Dame

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ABSTRACT

The Standard Model of physics provides a description of matter in the universe, but fails to reproduce many unexplained features, such as neutrino oscillations and the matter-antimatter asymmetry. One avenue to constrain physics beyond the Standard Model is via the precise determination of the V_{ud} matrix element of the Cabibbo-Kobayashi-Maskawa matrix from the *ft*-value of superallowed mixed beta-decay transitions. Such tests however require the determination of the Fermi to Gamow-Teller mixing ratio, which is currently unknown for all but five mixed mirror transition nuclei. At the University of Notre Dame a project is underway to develop a Paul trap devoted to the measurement of this elusive quantity. The design and goals will be presented.

1. Motivation

Current efforts to probe the limits of the Standard Model (SM) include precision testing of the Cabibbo-Kobayashi-Maskawa (CKM) matrix that relates a quark's eigenstates under the weak interaction to its EM and strong mass eigenstates [1]. Under the SM this matrix should be unitary and a violation of this could be the consequence of new physics, such as missing quark generation, new bosons, or even supersymmetry. One precise test of CKM matrix unitarity is the sum of the top row of the matrix $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$ where V_{ud} relates the up and down quarks involved in electroweak transitions and V_{us} and V_{ub} relates the up quarks to the strange and bottom quarks, respectively. The precise determination of this matrix element can be obtained from four types of decay: pion decay, neutron decay, superallowed mixed decay, and superallowed pure Fermi decay [2].

Superallowed pure Fermi decays are currently the most precise determination of V_{ud} and thus the most stringent tests of the normalization of the top row of the CKM matrix. Still, these results should be confirmed from other types of decay as any conflicting results could be the result of new physics or previously unknown systematic effects. The decay of the pion and the neutron are the simplest to interpret since they do not need nuclear structure corrections. However, they both present unique experimental challenges. Ambiguity in the neutron lifetime and the very weak branching ratio of the pion superallowed decay inhibit the ability to precisely determine the *ft*-value. For superallowed mixed transitions, these challenges are not present and there are numerous nuclides that decay in this manner. V_{ud} can however be extracted for only five mixed mirror transitions (See Fig. 1) due to a missing experimental quantity, the Fermi to Gamow-Teller mixing ratio ρ [3]. At the University of Notre Dame (UND) the Superallowed Transition BEta NEutrino Decay Ion Coincidence Trap (St. Benedict) is being developed to measure the mixing ratio for mirror nuclides of interest. As shown in Fig. 2, St. Benedict will primarily be a large volume gaseous ion catcher, a novel double-funnel extraction and focusing system, a radio-frequency quadrupole (RFQ), and a Paul trap. The radioactive isotopes will be produced with the *TwinSol* radioactive ion beam facility at the UND which creates radioactive species in-flight using transfer reactions in inverse kinematics [4]. St. Benedict will potentially expand the list of isotopes with known mixing ratios from the isotopes shown in Fig. 1 to include a variety of nuclei between ^{11}C and ^{41}Sc, where nuclei such as ^{11}C and ^{17}F have already been produced in significant quantities at *TwinSol*. The more flexible beam schedule at the UND gives a competitive advantage to perform this type of measurement where other interesting effects such as the possible presence of scalar current in the decay can be probed.

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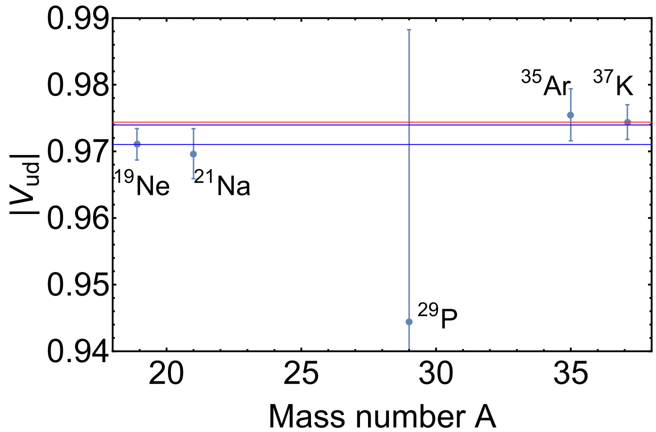

Fig. 1. The V_{ud} values from isotopes for which is has been measured from superallowed mixed decays. The blue bands represent the accepted average value for V_{ud}. For comparison, the red bands show the accepted V_{ud} value for pure Fermi transitions.

2. St. Benedict

The first component of St Benedict, the gas cell ion catcher, was originally built and operated at Argonne National Laboratory [5]. The cell will be operated at ~100 mbar of ultra-pure helium. Fast ions from *TwinSol* will enter the gas cell through a thin foil window. Once within the gas cell, the fast ions will thermalize via collisions with helium atoms. These ions are then transported using an electric field to a 1.3 mm diameter orifice. Along the walls of the gas cell, a radio-frequency (RF) carpet is employed to help transport the ions while also preventing their collision with the chamber wall. Upon reaching the extraction orifice, they are typically expelled at supersonic speeds.

Upon exiting the gas cell, the ions are collected and transported using a system of two differentially pumped RF funnels, whose design is identical to that described in [6]. The ions are efficiently transported through the 1st RF-only funnel operating at a background pressure of ~3 mbar and then extracted into high vacuum conditions (~0.001 mbar). Efficiencies with this design are expected to be better than 90%. A detailed simulation has been performed and the gas jet profile is shown in Fig. 3.

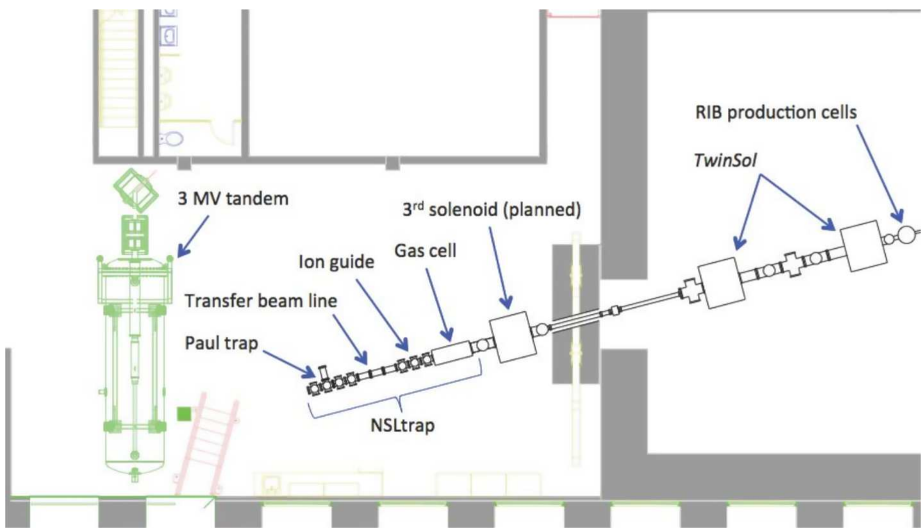

Fig. 2. Schematic drawing of the St. Benedict apparatus. The radioactive ions are created via *TwinSol*, stopped by the gas cell, transported to the RFQ through the double funnel system where they are collected and bunched, and finally deposited into the Paul trap.

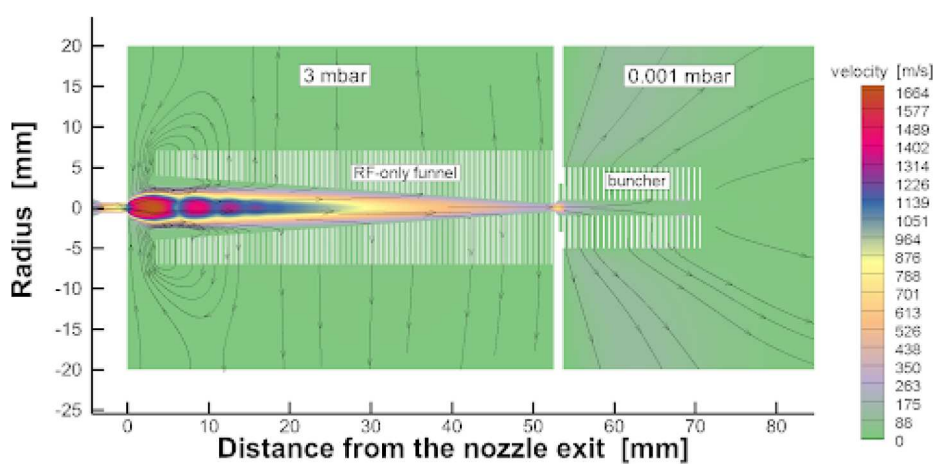

Fig. 3. A schematic design of the double-funnel system combined with the results of a gas dynamic simulation for the helium velocity flow field.

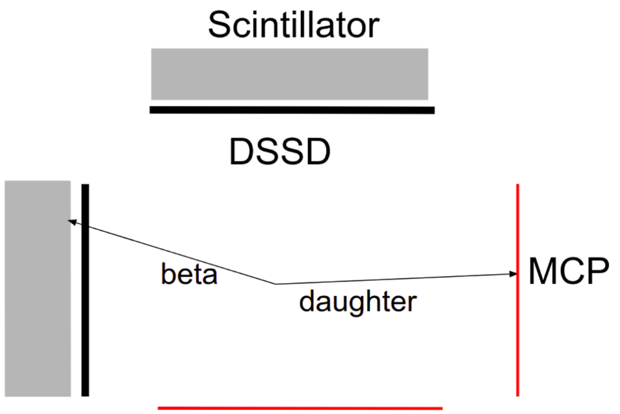

Fig. 4. A schematic of the intended detectors to surround the Paul Trap. Note the DSSD and MCP are both position-sensitive.

From the double-funnel system the ions will be accelerated to ~2 keV and focused by an einzel lens into an RFQ cooler-buncher, which will be used to accumulate, cool, and bunch the beam [7]. The RFQ is comprised of 3 differentially pumped sections, each with four segmented rods on which an alternating RF signal is applied to radially focus the beam. This design was based on the EBIT cooler and buncher at the National Superconducting Cyclotron Laboratory.

Finally this bunched beam will be delivered to the Paul trap located at the end. Here the ion bunch is confined using a combination of alternating and static electric fields [8]. Along the radial axis, the detectors will be placed in a cross pattern (See Fig. 4). Two neighboring segments of the cross will be comprised of a double-sided silicon strip detector (DSSD) backed by a plastic scintillator to stop the high energy betas. This combination of detectors will enable the precise measurement of the energy and position of the betas. The opposing two segments will contain a position-sensitive micro channel plate detector (MCP) for the precise timing needed for the time-of-flight of the recoil daughter nuclei as well as their position. All this information will allow for the determination of the recoil time-of-flight, position, and energy spectra as well as over-constraining the full kinematics of the decay. From these data V_{ud} will be able to be extracted.

3. Conclusion

A precise determination of the unitarity of the CKM matrix could help pinpoint the insufficiencies of the SM. The most precise determination of V_{ud} currently comes from superallowed pure Fermi beta-decays, though superallowed mixed Fermi beta-decays provide another avenue to further refine the same theoretical corrections used in pure Fermi decays. Determination of V_{ud} from the mixed transitions however requires the determination of the mixing ratio which is only known for five mixed decaying nuclei. The St. Benedict ion trapping system is currently under design and construction at UND to determine ρ in more isotopes, extending the list beyond the five nuclei for which it is known.

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