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Development of the St. Benedict Paul Trap at the Nuclear Science Laboratory

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Abstract
There are various tests of the Standard Model aimed at probing new physics. One such test is to check the unitarity of the Cabbibo-Kobayashi-Masakawa matrix, with the most precise result given by the normalization of the top row. The precision of this result is limited by the uncertainty of the V_{ud} and V_{us} elements. The most precise result for V_{ud} is currently derived from the ensemble of superallowed $0^+ \rightarrow 0^+$ nuclear β decays, but the determination from other transitions is desirable to check theoretical calculations and the potential presence of unknown systematic contributions. Other candidates include neutron decay, pion decay, and the ensemble of nuclear mirror decays. While the neutron and pion decay present their own unique experimental challenges, the group of mirror decays require the precise determination of the Fermi to Gamow-Teller mixing ratio. This value can be extracted from a measurement of the β-ν angular correlation parameter, $\alpha_{\beta\nu}$, which is currently only known for five mirror decays. A new ion trapping system, St. Benedict (Superallowed Transition Beta-Neutrino Decay-Ion-Coincidence Trap), to be located in the Nuclear Science Laboratory at the University of Notre Dame is currently under construction and will ultimately aim to extract $\alpha_{\beta\nu}$ for more mirror decays. The focus of this work is on simulations that will guide the design of the Paul trap which will be used for the measurement.

Keywords Weak interaction · Linear Paul trap · Ion confinement

1 Introduction

The Standard Model (SM) provides a complex, but incomplete, description of matter in the universe. Some observations, such as the blatant matter vs. antimatter asymmetry, cannot

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be fully explained by the SM [1]. There are currently several research campaigns aimed at probing physics beyond the SM from various avenues on both the energy [2] and precision [3] frontiers.

The investigation of weak couplings in β decay has been an effective tool in the past for finding new physics such as parity violation [4]. As measurements of β decays become more precise, contributions which are currently thought to be forbidden may be found. For example, many experimental groups are currently searching for small admixtures of scalar (S) or tensor (T) couplings that would violate the current form of the SM, as it only includes vector (V) and axial-vector (A) couplings [5, 6]. The presence of such weak couplings can be investigated through precision measurements of the β-ν angular correlation. If these exotic contributions exist, they would impact precision unitarity tests of the Cabbibo-Kobayashi-Masakawa (CKM) matrix, which can probe for physics beyond the SM. A critical component for that test is the precise determination of the V_{ud} matrix element which requires precise knowledge of nuclear physics quantities [7].

The Cabbibo- Kobayashi-Masakawa (CKM) matrix [8] describes the mixing between quark mass and weak eigenstates using a 3 x 3 unitary rotation matrix given by:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}, \tag{1}$$

where d, s, and b represent the down, strange, and bottom quarks respectively, while their primed counterparts represent the weak eigenstates. The various V_{ij} components of the CKM matrix represent the probability amplitudes for specific transitions [7]. One important caveat is that this matrix describes a rotation, and therefore must be unitary.

The unitarity of the CKM matrix can be tested by looking at the normalization of individual rows or columns. The most precise test consists of taking the sum of the top row elements [7] :

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1. \tag{2}$$

Since most weak transitions conserve quark generation, the matrix is concentrated along the diagonal with smaller off-diagonal components. Therefore, the uncertainty in the unitarity of the top row is dominated by the transition probability between up and down quarks. This element, V_{ud}, is studied via β decay.

There are four experimental approaches stemming from β decay where the nuclear matrix element is simple enough to probe the strength of fundamental interaction driving the transition; neutron decay, pion decay, superallowed ($0^+ \rightarrow 0^+$) nuclear decays (later referred to as pure Fermi), and mirror nuclear decays (later referred to as mixed decays).

Neutron and pion decays draw special interest since there are no nuclear corrections to consider, however they both also offer their own challenges. The neutron is hard to handle on its own since it is neutral, which makes it experimentally challenging. The extraction of V_{ud} from neutron decay requires a difficult correlation measurement to identify vector current contributions distinctly from axial-vector currents [9]. There is also a large discrepancy in the current world value for the neutron's lifetime [10]. The pion β decay has a very small branching ratio, of about 10^{-8}, which makes it hard to determine precisely [9]. The most precise result for V_{ud} currently comes from the ensemble of pure Fermi decays [9].

The strength of the transitions, referred to as an ft value, can be directly related to G_v, the vector coupling constant for all semi-leptonic decays. V_{ud} is related to G_v according to $G_\mathrm{v} = G_\mathrm{F}\mathrm{V}_\mathrm{ud}$ where G_F is the Fermi coupling constant [11]. The β decay rate for pure Fermi decays can be expressed as:

$$ft = \frac{K}{{G_\mathrm{v}}^2 \, |\mathcal{M}_F|^2} \tag{3}$$

where $K/(\hbar c)^6 = 2\hbar\pi^3 \ln(2)/(m_e c^2)^5 = 8120.2776(9) \times \mathrm{GeV}^{-4}s$ and $|\mathcal{M}_F|$ is the Fermi matrix element which equals $\sqrt{2}$ for pure Fermi decays. ft values are meaningful experimental quantities that can directly test theory. As (3) shows, ft values can be written in terms of the nuclear matrix element, which encompasses not only the initial and final states but also the form of the interaction which governs the transition. ft values rely on three experimental quantities; the half-life of the parent nucleus, $t_{1/2}$, the total transition energy, Q_{ec}, and the branching ratio of the decay, R. The total transition energy is used to calculate the phase-space factor f, while the branching ratio and half-life are used to calculate the partial half-life t. By combining the phase-space factor with the partial half-life and considering some small nucleus dependent correction terms, the corrected $\mathcal{F}t$ value is defined as:

$$\mathcal{F}t = ft\,(1 + \delta_R')(1 + \delta_{NS} - \delta_C) \tag{4}$$

where the δ terms are the various corrections. δ_R' is the nucleus dependent radiative correction, δ_C is the isospin symmetry breaking correction, and δ_{NS} is the nuclear structure correction term [9].

Superallowed cases provide an outlet to simplify this calculation due to the simplicity of the transition. Since only the Fermi part of the Hamiltonian contributes to the interaction, all superallowed decays should have the same $\mathcal{F}t$ according to the conserved vector current hypothesis. They all equal:

$$\mathcal{F}t^{\,[0^+\to 0^+]} = \frac{K}{2\,{G_\mathrm{F}}^2\,{\mathrm{V}_\mathrm{ud}}^2\,(1 + \Delta_R)} \tag{5}$$

where Δ_R is the transition-independent radiative correction. These decays have been studied in depth and have provided the most precise result for V_ud [12].

To obtain a value for V_ud that is not only precise, but also accurate, a second subset of nuclear β decays can be studied in order to further examine the effect of the correction terms. Other than the pion or the neutron, the group of $T = 1/2$ mixed mirror decays provides such an opportunity. Mixed decays, however, are slightly more complicated than pure Fermi because there can be either vector or axial-vector currents involved. For this reason a fourth experimental quantity is required for determining V_ud, the Fermi to Gamow-Teller mixing ratio, ρ. The $\mathcal{F}t$ value is then expressed as:

$$\mathcal{F}t^{[\mathrm{mirror}]} = \frac{K}{{G_\mathrm{F}}^2\,{\mathrm{V}_\mathrm{ud}}^2}\frac{1}{(1 + \Delta_R^V)(1 + \frac{f_A}{f_V}\rho^2)} \tag{6}$$

where f_A and f_V are the statistical rate functions for the axial-vector and vector parts of the interaction [11]. Since ρ is only known for five of the ~ 20 mixed mirror decays, the St. Benedict project is being developed to measure ρ for more nuclei through a precision measurement of the β-ν correlation coefficient $a_{\beta\nu}$. The St. Benedict ion trapping system will be located behind the University of Notre Dame Nuclear Science Laboratory TwinSol facility. It will comprise a large volume gas catcher to stop the 10-30 MeV radioactive ion beam from TwinSol, followed by a RF funnel system to guide the ions into a RFQ cooler and buncher before injection into the Paul Trap. A complete description of the components prior to the Paul trap is given in [13]. The remainder of this article will focus on the current status of the Paul trap development.

2 The measurement

The Fermi to Gamow-Teller mixing ratio can be determined from a measurement of either the β-ν angular correlation parameter $a_{\beta\nu}$, the β asymmetry parameter A_β, or the ν asymmetry parameter B_ν. Sensitivity studies of the determination of ρ from these various correlation coefficients have shown that generally a measurement of $a_{\beta\nu}$ would result in the most precise values of V_{ud} [14]. $a_{\beta\nu}$ is a coefficient in the β decay rate equation which, for an allowed decay, is given by [6]:

$$W \propto F(Z, E_e)\, p_e E_e (E_0 - E_e)^2 \left[1 + a_{\beta\nu} \frac{\mathbf{p_e} \cdot \mathbf{p_\nu}}{E_e E_\nu} + b \frac{m_e}{E_e}\right] \tag{7}$$

where $F(Z, E_e)$ is the Fermi function, E is total energy, p is momentum, the subscript e and ν denote whether the quantity is referring to the positron or the neutrino, E_0 is the end-point energy, m_e is the electron mass, and b is the Fierz interference term which equals 0 according to the SM [6]. $a_{\beta\nu}$ is therefore extracted by measuring the decay spectrum and extracting these fitting coefficients. Experimentally, the energy and position of both the recoiling nucleus and positron as well as the time of flight information for the recoil will be recorded. This will allow for the determination of the energy spectrum of the positron as well as over constraining the kinematics of the decay allowing for a systematic study of the system. In order to precisely measure the shape of the spectrum, the radioactive nuclei must be confined to a well-defined region of space and, after the decay, the emitted particles should be allowed to move freely to the detectors. This can be accomplished with an ion trap. Although the ideal hyperbolic shape for an ion trap in terms of ion confinement is well known, it is not useful in this case since it would interfere with the trajectory of decay products. For this reason, a linear Paul trap geometry which minimizes scattering of decay products is currently being investigated. Simulations have been developed to study ion confinement and determine the superior electrode geometry for this measurement.

The simulations will investigate Paul traps which use dynamic electric fields to trap charged particles to a small cloud at the center or the trap. The Paul trap being developed for the NSL will be modeled after the β-decay Paul Trap (BPT) which is currently in use at Argonne National Laboratory [6]. The BPT is designed with thin segmented blade electrodes on which a RF signal is applied, allowing the ions to be held in a well-defined region of space. The specific geometry of the BPT is advantageous for correlation measurements due to the fact that the electrodes occupy a small solid angle, which enables maximum detector coverage. For this reason, the basic planar design of the electrodes may be mimicked for the new trap, however the use of thin rods, or wires, is also under investigation.

3 Trap simulations

A series of simulations have been developed to study the efficiency of various electrode geometries using SIMION [15] and Geant4 [16]. In these simulations the cooling of a trapped ion was studied for various electrode shapes. We also investigated the impact of the electrode structure on the scattering of decay products from the center of the trap. There were two basic electrode geometries which were used for this study. The planar electrode geometry, referred to as blades, such as the one in use with the BPT, as well as a cylindrical geometry, referred to as wires. Visual examples of these electrodes are given in Fig. 1. Both of these electrode geometries are more advantageous than the ideal hyperbolic geometry for our application as they minimally obstruct the solid angle between the ion cloud

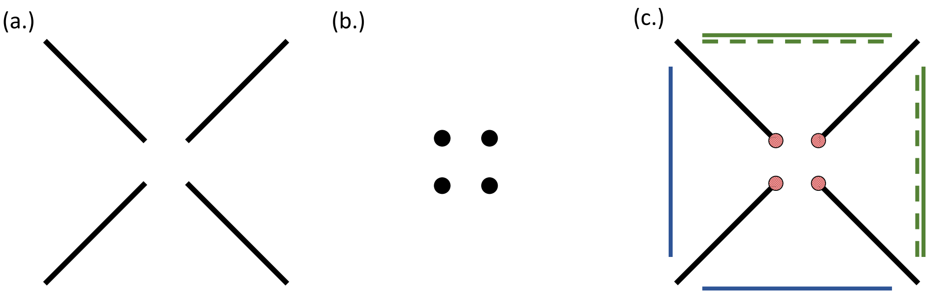

Fig. 1 Cross sectional views of electrode geometries under investigation. Panel **a** depicts the planar "blade" electrodes, while panel **b** shows the cylindrical "wire" electrodes. Panel **c** shows both electrode geometries overlaid in the same image along with the detector geometry. Note that in this figure the diameter of the wire in (**b**) and (**c**) is exaggerated for clarity. In reality the diameter of the wire will be comparable to the blade thickness. The green lines represent a double sided strip silicon detector which will be used to detect β particles, while the blue lines represent the placement of a position sensitive MCP used to detect recoil nuclei

and the detectors. The two questions that these simulations aim to answer are whether the reduction from blades to wires results in a substantial increase in cloud size, and whether the decrease in total material between the ion cloud and detectors results in fewer false events being registered even though there is similar solid angle coverage.

3.1 Ion confinement

Ion confinement in a well-defined region of space is a requirement for our measurement due to the fact that the location of the decay event needs to be well constrained to measure the angular correlation of decay products. A SIMION simulation was created in order to test the ability for the different trap geometries to confine an ion in the center of the trap. To do this, ions were generated near the center of the trap with an energy normally distributed about 0.5 eV with a standard deviation of 0.1 eV, and a random direction of momentum. The initial position was also randomly generated using a Gaussian distribution centered on the center of the trap with a standard distribution of 1 mm in each dimension. These cloud characteristics were based on measurements done with the BPT [6]. An oscillating time dependent voltage applied to each electrode provided the three-dimensional confinement. The trap was also filled with helium gas at $1.3 * 10^{-5}$ mbar in order to cool the ion via collisions (assumed to be hard-sphere in the simulation) with the residual gas while being confined. Particle trajectories were calculated for 50 milliseconds after the birth of the ion. The standard deviation of ion displacement from the center of the trap as a function of time for a group of 500 particles is plotted in Fig. 2 for the two different trap geometries under consideration.

The simulations show that both electrode geometries are able to confine ions in the center of the trap. This is depicted by the plots in Fig. 2. When the ion cloud is initially generated, at time 0 as shown on the plots, the particles have an average displacement of 1.5 - 2.5 mm depending on which dimension is observed. As time progresses, and the ions collide with the residual helium gas in the chamber, they lose their energy, as seen by the decaying nature of the average ion displacement as a function of time. For both trap geometries under consideration, the average ion displacement from the center of the trap decreased by a factor of about 1.5 in the first 50 ms, as depicted in Fig. 2. There were also various wire diameters considered. The advantage to using wires is that they can be made much thiner than the

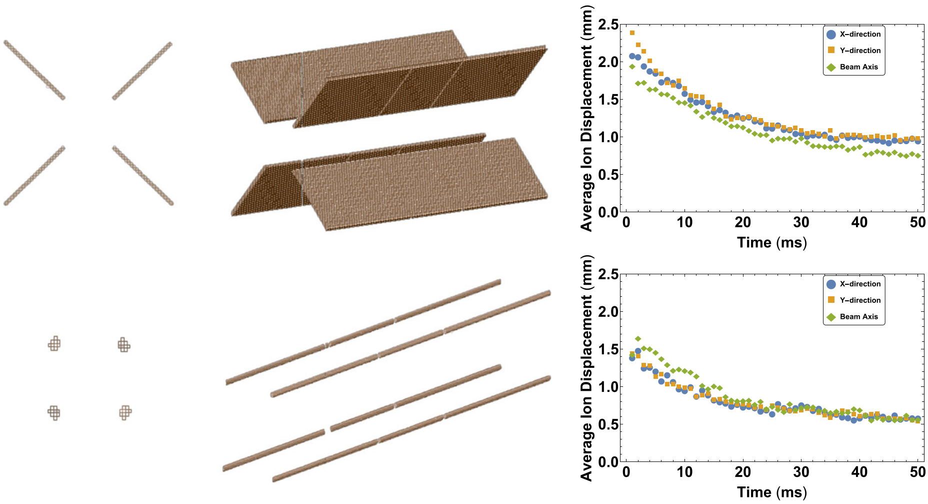

Fig. 2 Cross-sectional and three-dimensional views of the electrode geometries are shown in the SIMION graphical user interface, along with plots depicting cooling of the cloud as a function of time. The top three images depict the blade geometry, while the bottom three show the wire geometry. The results are for a blade thickness of 2 mm and a wire diameter of 0.5 mm

blades and still be held in place by tension, while the blades have to be a certain thickness to ensure they stay straight. Wires with a diameter equal to the thickness of the plates under consideration (2 mm) had similar trapping capability, while thinner wires (0.5 mm) required a larger RF amplitude to achieve a similar cloud size in the same amount of time (900 Vpp vs. 450 Vpp).

3.2 Scattering

With the ability to confine ions using both electrode geometries established, the next consideration was the impact of the different geometries on the flight trajectory of decay products from the origin of the decay to the detector. One source of error for this experiment arises from false events being registered as a result of β particles scattering off the physical material which forms the trap. These particles can scatter towards one of the detectors, and if the timing occurs in coincidence with a particle resulting from a different decay, the event can falsely register and impact the result. A Geant4 simulation was therefore created to determine which geometry reduces the effect of beta scattering. Visual representations of simulations are shown in Fig. 3.

β particle energies were generated according to the β decay spectrum for a decay of interest, ^{17}F in this case, and then input to the Geant4 simulation. From here a detector was modeled and the simulation was carried out both with, and without, the electrodes in place. Only one detector was used in this test since the symmetric design will yield the same result in all locations. The energy spectrum of β particles which reach the detector was recorded for the various trap geometries along with the result with no electrodes present. It was observed that there was a 5% increase in events for the blade geometry, while there was a 3% increase in events with the wires present if the wires have diameter equal to the thickness of the blades. This is interpreted as a majority of the ions being scattered directly off the front edge of the electrode, so the main contributor is due the solid angle covered

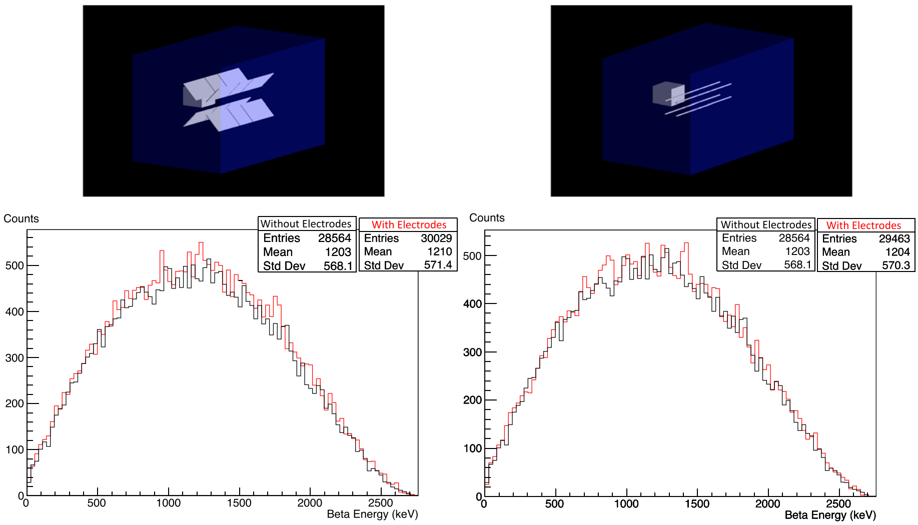

Fig. 3 Electrode geometries shown in the Geant4 graphical user interface, along with plots depicting the change in spectra with and without the electrode geometry present. The left panels represent the blade geometry, while the right panels represent the wire geometry. The rectangular region in the background of the rectangular region represents the placement of the detector

by the electrodes. Therefore, there is only a noticeable decrease in scattering with the wire geometry when thinner wires are used. This also does not consider that the wires require a support structure to hold them under tension which may add a certain amount of solid angle coverage, depending on the design. This is different than the blade design, which can be designed to have supports housed behind the detectors. With the proper design for the wire electrode support, and thin enough wires, the new design may reduce the number of false events which get registered by the data acquisition system.

4 Conclusion

The St. Benedict trapping system, which is currently under construction at the NSL, will be dedicated to measuring the β-ν angular correlation parameter allowing for the determination of the Fermi to Gamow-Teller mixing ratio for light mixed-mirror decays with relatively long half-lives. This facility will allow for ample beam time for this measurement, which is necessary with the lifetime of these isotopes. While components for St. Benedict such as the cooler-buncher and gas catcher have been assembled but not tested, the ion trap is still under development. Both blade and wire ion traps prove to have advantages and disadvantages. A wire trap would decrease scattering, provided the support structure to hold the wire under tension did not add too much material, while the blade design creates a marginally better field for ion confinement away from the beam axis. When the trade offs are determined, and properly managed, the support structure and housing will be designed and manufactured.

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