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Stopped, bunched beams for the *TwinSol* facility

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Abstract
Tests of the unitarity of the Cabbibo-Kobayashi-Masakawa (CKM) matrix offer an important avenue for constraining the Standard Model of the electroweak interaction. Several methods are currently used to determine V_{ud}, the largest element in the top-row normalization test. One such method is through the study of superallowed $T = 1/2$ mixed mirror transitions, which offers a complementary method to the current most-precise value that is determined from superallowed pure Fermi $0^+ \rightarrow 0^+$ transitions. The precision currently achievable by this method is currently limited by the very low number of transitions for which the Fermi-to-Gamow-Teller mixing ratio ρ has been measured. St. Benedict, the Superallowed Transition Beta-Neutrino Decay-Ion-Coincidence Trap, is currently under development at the University of Notre Dame's Nuclear Science Laboratory, and intends to determine ρ for a range of new isotopes through measurements of the β-neutrino asymmetry parameter $a_{\beta\nu}$ using a linear Paul trap. In order to trap these ions, the fast, continuous secondary beam separated by the *TwinSol* twin solenoid separator must be thermalized and bunched. The system through which this will be done will feature a large-volume gas cell in which the ions will be thermalized, a double-RF-funnel-based ion guide system for the extraction of the ions, and a radiofrequency quadrupole (RFQ) to provide cooled ion bunches for capture in the Paul trap.

Keywords Fundamental symmetries · Ion trapping · Mirror transitions · Radioactive ion beams · RFQ · Beam cooling

1 Introduction

Testing the unitarity of the Cabbibo-Kobayashi-Masakawa (CKM) matrix offers an important avenue for constraining physics beyond the Standard Model. Several methods are used

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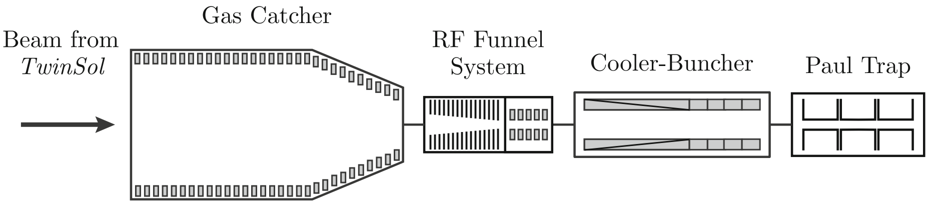

Fig. 1 Schematic diagram of the design of St. Benedict, showcasing the four major elements: the gas catcher, RF funnel extraction system, cooler-buncher, and Paul trap

to determine V_{ud}, the largest of the three elements going into determining the CKM matrix unitarity from the normalization of the top row [1, 2]. Thanks to extensive experimental efforts, the superallowed $0^+ \rightarrow 0^+$ pure Fermi transitions provide the most precise value of V_{ud} and thus the most stringent test of CKM matrix unitarity. However, alternate approaches are desirable to test for unknown systematic effects or even new physics; one such approach is to use superallowed mixed mirror transitions [3]. Determining the corrected $\mathcal{F}t$-value in these systems is more challenging, as it requires the determination of the Fermi to Gamow-Teller mixing ratio ρ, which has currently been done for only five medium-mass nuclei of interest: ^{19}Ne [4], ^{21}Na [5], ^{29}P [6], ^{35}Ar [7, 8], and ^{37}K [9, 10]. A recent program at the University of Notre Dame's Nuclear Science Laboratory has demonstrated the production of radioactive ion beams of several superallowed mixed mirror transition nuclei using the *TwinSol* twin solenoid separator [11] with new half-lives, necessary for the calculation of the partial half-life t in the $\mathcal{F}t$ value, having been measured for ^{11}C [12], ^{17}F [13], and ^{25}Al [14]. Based on the most recent experimental results on the five superallowed mixed mirror transitions for which ρ is known, $V_{ud} = 0.9727(14)$ can be calculated [3, 10, 15], which is consistent with the value from the most recent review of superallowed pure Fermi transitions, $V_{ud} = 0.97412(21)$ [16] but a factor of seven less precise. St. Benedict, the Superallowed Transition Beta-Neutrino Decay-Ion-Coincidence Trap, is currently being developed for installation after *TwinSol*; it will use a Paul trap to measure the beta-neutrino correlation angle $a_{\beta\nu}$ and thus determine ρ for the isotopes for which it is not currently known, allowing a significant increase in the precision of the mixed mirror V_{ud} value [17].

2 Facility design

St. Benedict will make use of rare isotope beams produced at the *TwinSol* facility. These beams are produced by transfer reactions of heavier primary beams on lighter gas targets. The stable primary beam is created using an FN Tandem accelerator with a maximum terminal voltage of 10 MV. After the transfer reactions, the secondary beam is separated from the remaining primary beam and other transfer reaction products using the *TwinSol* twin solenoid separator. This fast secondary beam must be decelerated, thermalized, and bunched before it can be injected into and trapped by a Paul trap. Figure 1 is a schematic diagram of the proposed design of St. Benedict, showcasing the major elements. The first three major elements, the gas catcher, RF funnel system, and cooler-buncher, will produce the necessary stopped, bunched beams for injection into the fourth element, the Paul trap.

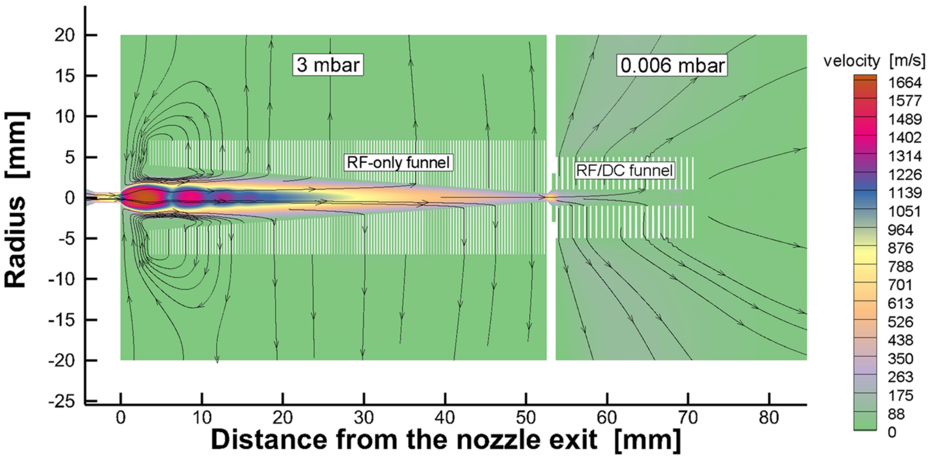

Fig. 2 Gas dynamic simulation of the double-RF-funnel extraction system for the gas velocity flow field

2.1 Gas catcher

In order to thermalize the incident secondary beam from *TwinSol*, which will have an energy of $\sim$ 30 MeV, a set of thin degraders and a helium-gas filled gas catcher will be used, similar to the setups used at other in-flight production facilities [18–22]. The gas catcher that will be used was originally built and operated at Argonne National Laboratory's ATLAS facility where it was previously used in Area II for mass measurements using the Canadian Penning Trap [23, 24] and $a_{\beta\nu}$ measurements [25, 26] and β-delayed neutron spectroscopy [27] using the Beta-decay Paul Trap. It is composed of a 84 cm long volume filled with up to 100 mbar of high-purity helium gas with a 1.9 mg/cm^2 HAVAR window through which the ions will be injected. Collisions with the helium gas thermalize the fast ions and recombine them to a 1+ electrical state. A combination of gas flow and a DC field will guide the thermalized ions towards the extraction region. To prevent losses due to collisions with the walls of the gas catcher, RF carpet electrodes provide a repulsive force. SRIM [28] calculations have demonstrated that additional degraders will be necessary to stop the ions in the volume of gas. Approximately 35 μm of Mylar will be used to provide this additional stopping power, with the precise thickness necessary varying based on both the energy and mass of the incident ions.

2.2 RF funnel system

Following extraction of the ions from the gas catcher, it is necessary to transport the ions from the high-pressure region near the gas catcher to the substantially lower operating pressures of the rest of St. Benedict while minimizing losses. This will be done using a system composed of two RF funnels that is very similar to the extraction system that have been proposed in [29] and now is under development for a new laser ablation ion beam source for LASPEC Collaboration [30] at TU Darmstadt. These two funnels will guide and collimate the ions as they travel through the region of decreasing pressure. The first funnel will be composed of 140 circular electrode plates, each 0.1 mm thick, and operated with alternating plates at opposite RF phases. Differential pumping and a single dry vacuum pump

Table 1 Specifications of the double-RF-funnel extraction system

Parameters	First funnel	Second funnel
Entrance Aperture Diameter	8 mm	2 mm
Exit Aperture Diameter	1 mm	2 mm
Electrode Plate Width	10 mm	10 mm
Electrode Thickness	0.1 mm	0.2 mm
Inter-Electrode Spacing	0.25 mm	0.5 mm
Number of Electrodes	140	25

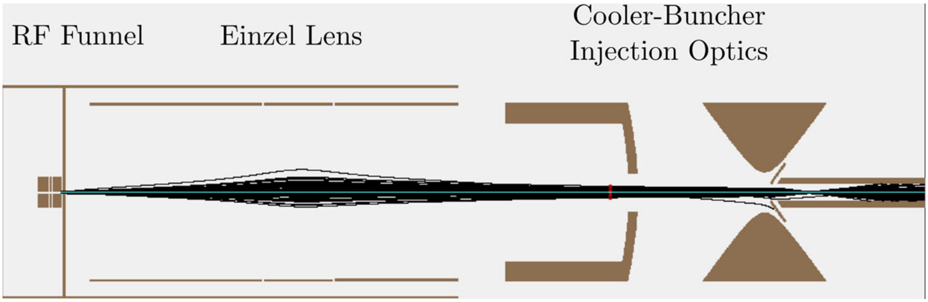

Fig. 3 SIMION simulation of ion optical transport from the double-RF-funnel system to the Cooler-Buncher using an Einzel lens

will maintain a pressure of 3 mbar in the funnel if the gas catcher is operated at a pressure of 100 mbar. A second funnel, composed of 25 electrodes, each 0.2 mm thick, and operated with both alternating opposite RF phases and a DC gradient, will further reduce the operating pressure to 0.006 mbar with a 350 L/s turbomolecular pump. Simulations of extraction through this design have shown efficiencies better than 90%. Figure 2 shows the results of a gas dynamic simulation and showcases the design, operating pressures, and average gas velocity in the volume, while Table 1 shows the specifications of the elements of the two funnels.

2.3 Injection into the Cooler-Buncher

The second RF funnel is followed by another differential pumping barrier, which is a 2 mm long hole with a diameter of 2 mm. After this barrier, the pressure is further reduced to 3.4×10^{-6} mbar. In order to maximize the injection efficiency into the Cooler-Buncher located downstream of the double-RF-funnel system, it is necessary to focus the ions using an Einzel lens. SIMION [31] simulations of this region were performed, including both the potentials of the involved electrodes and the expected pressures of the various regions; a sample simulation can be seen in Fig. 3. It was found that a focusing potential of 1.2 kV will allow for better than 95% transmission through this region, and will adequately match the phase-space acceptance ellipse for the Cooler-Buncher, as seen in Fig. 4, providing for maximum acceptance.

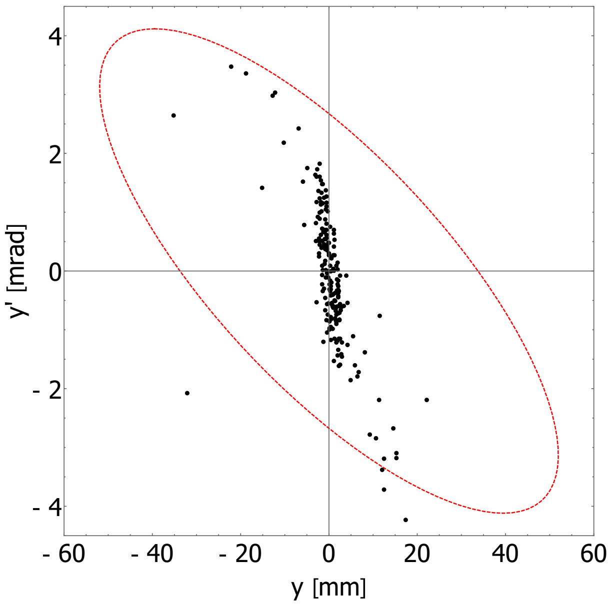

Fig. 4 Comparison of emittance of ion beam on injection into the Cooler-Buncher (black points; $\epsilon_{RMS} = 21\pi$ mm mrad) with the acceptance of the Cooler-Buncher (red, dashed line; $\epsilon = 139\pi$ mm mrad)

2.4 Cooler-buncher

The final major element of St. Benedict before the Paul trap is a cooler-buncher. A cooler-buncher is a buffer-gas-filled linear radiofrequency quadrupole (RFQ) trap designed to convert a high-emittance continuous source into low-energy, low-emittance ion bunches [32]. Collisions with the buffer gas reduce the transverse emittance and energy spread, providing a damping force and "cooling" the ions. RFQs are formed of four equidistant elongated electrodes that are typically segmented, allowing the application of the potential gradient that creates a weak static electric field which drags the ions axially to the end of the cooler-buncher [33]. An alternating electrical potential in the radio-frequency regime is also applied with opposite polarity on adjacent RFQ rod, resulting in a radially-confining pseudo-potential. The segmentation of the RFQ electrodes also allow the creation of a potential well that accumulates or "bunches" the ions; these bunches are then released downstream by switching the trap potential. Cooler-bunchers are currently in use at many facilities in this role, including the CARIBU [34], ISOLTRAP [32, 35], JYFLTRAP [36], LEBIT [33], SHIPTRAP [37], TITAN [38], and TRIGA-SPEC [39, 40] facilities. The cooler-buncher design selected for use in St. Benedict is currently in use at the NSCL before their EBIT [41] and is based on the BECOLA design [42, 43]. It includes several novel design features designed to optimize performance.

To maximize transmission through the cooler-buncer, injection losses must be minimized. A hyperboloid ring electrode and cone electrode are used to create a cylindrically-symmetric quadruple potential that decelerates and focuses the beam on injection. Furthermore, the first section of RFQ electrodes are flared away from the beam axis before

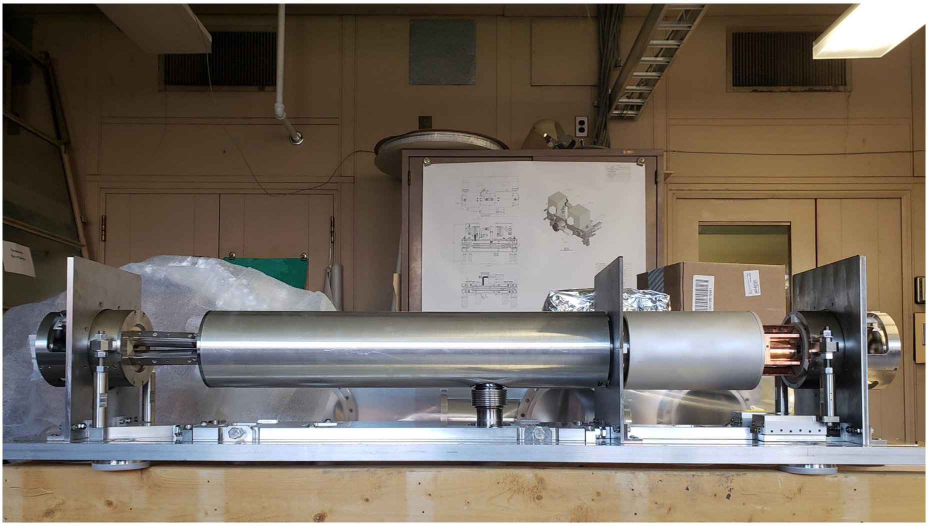

Fig. 5 Photograph of the assembled internal structure of the cooler-buncher before the wiring of the electrodes, including enclosed cooling section, differential pumping barriers for the different pressure regions, and assembly of the electrode structure including flared injection RFQ electrodes and diagonally-split cooling region electrodes. Beam travels from left to right

tapering back inwards, so that the beam can expand slightly after focusing without losses while maintaining radial confinement. High pressure buffer gas results in shorter cooling times; however, it can also result in collision-induced "reheating" in the bunching section. In order to provide high-pressure helium for cooling but lower pressures for bunching, these two sections of the cooler-buncher are separated using a series of PEEK disks, which provide differential pumping between these two regions. The longitudinal static potential well needed to provide axial confinement is often done by segmenting the RFQ electrodes and applying different potentials; in this design, however, the electrodes are segmented into two wedges to which different potentials are applied, such that the ions experience the same longitudinal drag with fewer electrodes. The oscillating RF potential is often applied to the RFQ electrodes through a series of either capacitors or transformers, thus isolating the static potentials from the RF signal. Here, a common RF "backbone" for RFQ electrodes to which the static RFQ electrodes couple capacitively is used instead. These two changes simplify the construction and maintenance of the RFQ electrodes.

The construction of the cooler-buncher has been completed. Figure 5 shows the finished electrode assembly, after which the wiring of the electrodes was completed and the RF circuitry, which consists of a tunable resonant LC circuit, was tested. Further commissioning awaits the assembly of the upstream elements of St. Benedict. A discussion of the final major element of St. Benedict, the Paul trap, can be found in D.P. Burdette's contribution to these proceedings [44].

3 Conclusion

In summary, St. Benedict, the Superallowed Transition Beta-Neutrino Decay-Ion-Coincidence Trap, aims to determine the Fermi-to-Gamow-Teller mixing ratio through measurements of $a_{\beta\nu}$ for superallowed mixed mirror transitions at the University of Notre Dame's Nuclear Science Laboratory, and thus expand the ensemble of such decays that can contribute to the determination of V_{ud}. In order to do this, the fast, continuous rare isotope beams separated by the *TwinSol* twin solenoid separator will need to be decelerated, thermalized, and formed into bunches suitable for trapping in a linear Paul trap. This will be done using a gas catcher to decelerate and thermalize the fast beam, a double-RF-funnel system to extract the ions, and a cooler-buncher to further cool and bunch the ions.

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