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Construction of St. Benedict

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ABSTRACT

The Superallowed Transition Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict) is currently under construction at the University of Notre Dame Nuclear Science Laboratory. It is designed to measure the beta-neutrino angular correlation parameter in superallowed mixed beta-decay transitions between mirror nuclei in order to extract the Fermi-to-Gamow Teller mixing ratio and test theoretical corrections entering in the determination of the V_{ud} element of the Cabibbo–Kobayashi–Maskawa quark mixing matrix. St. Benedict includes a large volume gas catcher to thermalize the radioactive ion beam from *TwinSol*, a differentially-pumped extraction system, a radiofrequency quadrupole ion cooler and buncher, and a Paul trap for the observation and detection of the β decay products. The status of each of these components will be presented.

1. Introduction

Nuclear β decays provide a unique avenue for testing the electroweak part of the Standard Model through precision measurements [1]. Physics beyond the Standard Model would manifest itself in these transitions through a variety of possible effects, including a non-unitarity of the Cabibbo–Kobayashi–Maskawa quark mixing matrix, scalar or tensor currents, and interactions involving right-handed neutrinos [2]. Probing these various effects in superallowed mixed β decay transitions can be achieved through precision measurement of the beta-neutrino angular correlation parameter $a_{\beta\nu}$ [3]. As such, we are currently constructing the Superallowed Transition Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict) [4,5] at the Nuclear Science Laboratory (NSL) of the University of Notre Dame (UND).

2. RIBs production at the NSL

The NSL has been producing radioactive ion beams (RIBs) since the 1980's [6], and has undergone several upgrades including the implementation of a dual solenoid system (*TwinSol*) for better RIBs separation [7] and a multi-target system [8]. More recently, a 15° switching magnet has been added after *TwinSol*, as indicated in Fig. 1, to allow for the permanent installation of two new systems receiving RIBs on separate beam lines: St. Benedict and *TriSol* [9,10]. Several RIBs have been produced over the past several years, including the isotopes undergoing a superallowed mixed transitions listed in Table 1.

3. St. Benedict

St. Benedict includes four major components, shown in Fig. 2, that take the fast ions from *TwinSol* and ultimately confine them to measure the $a_{\beta\nu}$ of the decay. First, the RIBs produced by *TwinSol* are thermalized in a large volume gas catcher, then they are transported through two separate differentially-pumped volumes; one using a radio-frequency carpet and the other a radio-frequency quadrupole (RFQ) ion guide. Transported beams are then injected into a RFQ trap to create cool ion bunches for injection into the Paul trap.

4. Gas catcher

The role of the St. Benedict gas catcher is to stop the 10–40 MeV beam from *TwinSol* and then extract it with sub-keV energy. The beam first loses most of its energy when passing through a thin mylar degrader and the aluminum entrance window. Then, the ions enter the gas catcher, where they thermalize via collisions with helium atoms at

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Table 1
A table of isotopes undergoing a superallowed mixed transition with established production rates with the *TwinSol* separator and their respective half lives [11].

Isotope	Half-life (s)	Rate (pps/pμA)
^{11}C	1220.41(32)	2.4×10^5
^{13}N	597.88(23)	8.1×10^5
^{15}O	122.27(6)	5.0×10^6
^{17}F	64.366(26)	1.5×10^6
^{25}Al	7.1674(44)	3.0×10^5
^{29}P	4.1031(58)	1.0×10^5
^{33}Cl	2.5059(25)	9.0×10^3
^{41}Sc	0.5962(22)	4.0×10^3

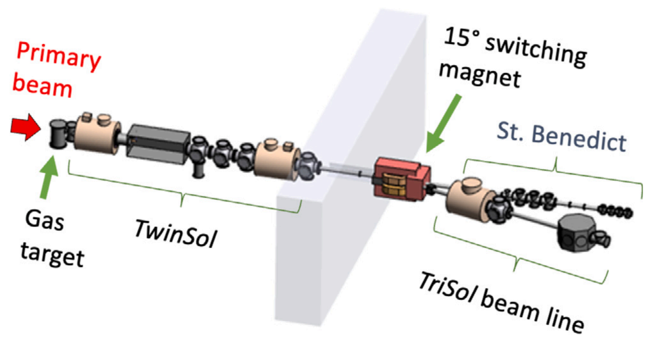

Fig. 1. Schematic diagram of the radioactive ion beam lines at the University of Notre Dame Nuclear Science Laboratory. Indicated are the gas target and *TwinSol* on the left and on the right are the St. Benedict experiment and the *TriSol* beam lines after a switching magnet.

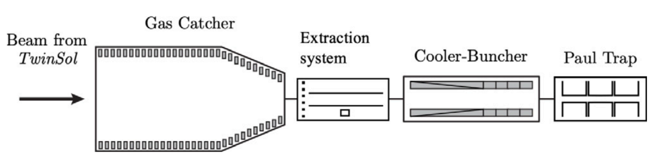

Fig. 2. Schematic diagram of the St. Benedict beam line showing the locations of the major components; the gas catcher, extraction system, cooler-buncher and Paul trap.

~100 mbar. Finally, a combination of a potential gradient and a time-varying signal at radiofrequency applied on electrodes transports the ions towards a nozzle, at which point they are evacuated by gas flow to the following chamber.

The St. Benedict gas catcher was a precursor to the CARIBU gas catcher [12] and was previously used at Argonne National Laboratory to provide RIBs to the Canadian Penning Trap [13] before being decommissioned. It is currently being recommissioned at the University of Notre Dame. The DC potentials have been tested, and up to 600 V has been applied to the entrance section. All three RF circuits have been impedance-matched such that no power is reflected, up to a 50 V amplitude at the electrodes. The gas catcher has also been leak-checked and pumped down to below 2×10^{-8} Torr using the configuration shown in Fig. 3. We are currently performing transport tests of potassium ions produced by a thermionic source located on the inside of the entrance side of the gas catcher. Upon the successful completion of these transport tests, the gas catcher will be moved to its final configuration behind the 15° switching magnet, where it will be commissioned using an ion beam from *TwinSol*.

5. Extraction system

Upon leaving the gas catcher, the ions are guided through two differentially-pumped chambers. In the first one, a RF carpet [14] will transport the ions using the ion surfing method [15] at ~3 mbar, into a second chamber housing an RFQ ion guide in a region with a pressure of ~2×10^{-3} mbar. The RF carpet has been commissioned using a potassium thermionic source and has been shown to achieved ~100% transport efficiency for pressures above 0.75 mbar in the presence of helium flow [16].

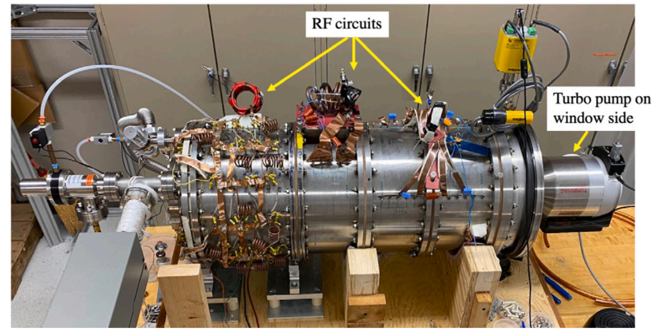

Fig. 3. A photo of the gas catcher configuration used during the vacuum tests.

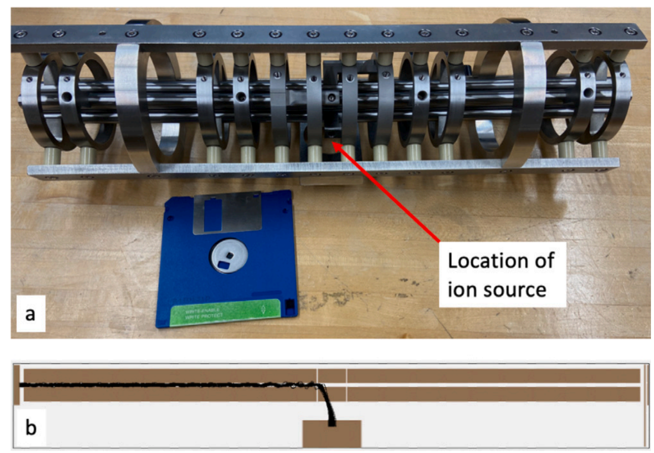

Fig. 4. (a) A photo of the St. Benedict ion guide with a 3.5” floppy disk for scale. (b) Ion optical simulation results demonstrating transport of ions from the off-line source.

The ion guide, shown in Fig. 4, has been designed and assembled. This ion guide includes a thermionic source placed off-axis, mid-way through the structure. Its beam will be directed through two of the central rods that form the quadrupole structure. Ion optical simulations indicate that >95% of the ions from the source can be transported along the structure. This ion source will provide off-line beam for testing downstream components of St. Benedict once they are installed at their final location after *TwinSol*.

6. Cooler and buncher

The St. Benedict cooler and buncher [17] converts the continuous beam from the extraction system into cooled bunches. Ions are cooled via collisions with helium atoms from a buffer gas at 10^{-2} mbar. The ions are confined radially by the pseudo-potential created by the RF applied to the quadrupole structure surrounding them. Segmentation of the structure allows for the application of a potential gradient that drags the ions through the cooling region and into the bunching section where the ions are accumulated in a potential well before being extracted as a bunch by rapidly switching the potential on two of the electrodes. The St. Benedict device is similar to the design of the FRIB EBIT cooler and buncher [18].

The off-line commissioning with a potassium thermionic source has been completed with the setup shown in Fig. 5, and demonstrated

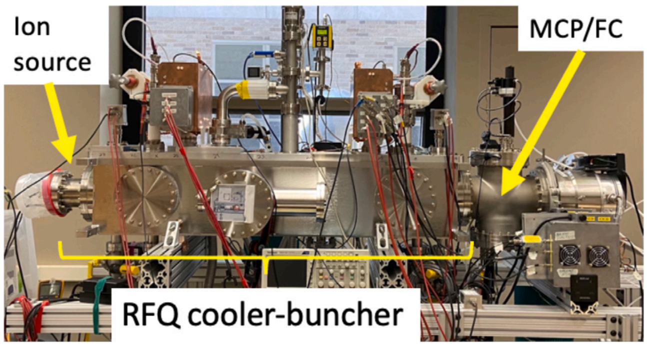

Fig. 5. A photo of the setup used for the off-line commissioning of the cooler-buncher.

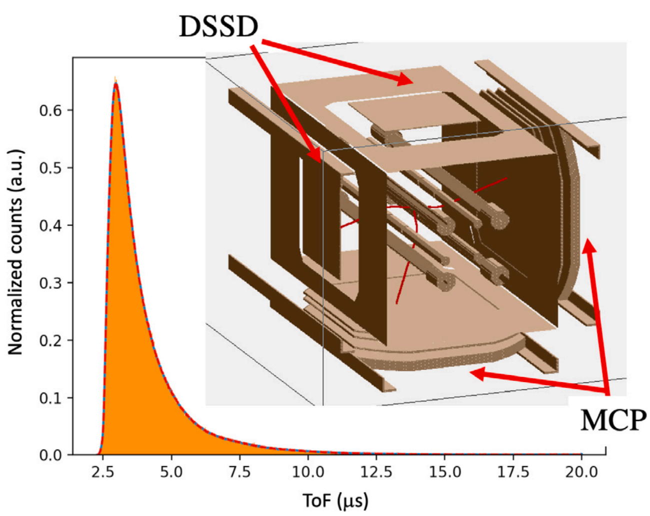

Fig. 6. Geometry of the Paul trap with. in red, sample trajectories of three ^{17}O ions for which the time-of-flight to a MCP detector is calculated. Also shown is the corresponding normalized time-of-flight distribution generated using SIMION [19] of 1.2 million ^{17}O ions. The parameter $a_{\beta\nu}$ can be obtained from fitting such distributions [20].

~80% of the beam gets from the source into the RFQ. All of those ions then get transported to the end of the device and are successfully bunched.

7. Paul trap

The St. Benedict Paul trap, a schematic of which is shown in Fig. 6, holds ions in free space and is surrounded by two position-sensitive micro-channel plates (MCP) and two double-sided silicon strip detectors (DSSD) backed by plastic scintillators attached to photomultiplier tubes (PMT) [21]. The DSSD will record the position of the emitted positron and the PMT its timing. The MCP, on the other hand, will measure the position and arrival time of the corresponding recoiling daughter nuclei of that decay. The $\beta-\nu$ angular correlation parameter $a_{\beta\nu}$ is then obtained by fitting the distribution [20] of differences between these times (referred to as time-of-flight) as shown in Fig. 6. Simulations that take into account the production rate and half-life listed in Table 1 indicate that a relative uncertainty on the $\beta-\nu$ angular correlation parameter $\delta a_{\beta\nu}/a_{\beta\nu} = 0.5\%$ can be achieved within 2 weeks for ^{15}O, ^{17}F, ^{25}Al, and ^{29}P.

8. Conclusion

St. Benedict aims to measure the beta-neutrino angular correlation parameter in superallowed mixed transitions in order to determine the Fermi-to-Gamow Teller mixing ratio and test calculation methods for the theoretical corrections entering into the determination of the V_{ud} element of the CKM matrix. St. Benedict will comprise four major components: a gas catcher, an extraction system, a RFQ cooler-buncher, and a Paul trap. All of these individual components are either already commissioned or nearing testing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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