TAMU-TRAP facility - program for the study of fundamental weak interaction

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Primary goal of the TAMU-TRAP facility is to test the Standard Model (SM) for a possible admixture of a scalar (S) or tensor (T) type of interaction in $T = 2$ superallowed $\beta-$ delayed proton emitters. This information will be inferred from the shape of the proton energy spectrum. The main component of the facility are an RFQ cooler/buncher for cooling and bunching the ions, a Penning trap system with two cylindrical Penning traps. Additional goals for this system are mass measurements, lifetime measurements, and $ft-$values. A brief overview of the TAMU-TRAP set-up and T-REX upgrade facility will be presented.

1. Introduction

The Standard Model (SM) in particle physics [1] describes accurately all observations in particle physics. It is comprised of the standard electroweak theory [2, 3] which couples the electromagnetic and the weak interaction, and the theory of strong interaction. This far ranging theory lacks however, a deeper and more satisfactorily explanation for many desired facts. The open questions includes the number of free parameters in the SM, the hierarchy of the fundamental fermion masses, the number of three particle generation, origin of parity (P) violation and combined charge symmetry (C) and parity (CP) violation.

Over the years many experiments, ranging from the low energy scale of nuclear $\beta-$ decay to the very higher energies at colliders have put the SM to the test, search, for possible deviation which could point out in which direction the model has to be extended. Several important properties of the weak interactions, such as parity violation [4] and the well known V-A structure of the interaction [5] were discovered in nuclear $\beta-$decay. Also today, precision measurements in nuclear and neutron $\beta-$decay continued to be an efficient tool to search for new physics beyond the standard electroweak model [6]. All experiments carried out till now can be explained by a time-reversal-invariant pure $V - A$ interaction with maximal violation of parity. Nevertheless, experimental error bars still leave sufficient room for the possible existence of other types of weak interaction in $\beta-$decay.

For allowed beta-decays the most general Lorentz invariant Hamiltonian for a four-fermion interaction allows for the existence of scalar (S), vector (V), axial-vector (A), tensor (T) and pseudoscalar (P) type contributions and makes an a *priori* assumptions about the parity and time-reversal properties of these [8, 9]:

$$H_\beta = \frac{G_F}{\sqrt{2}} V_{ud} \sum_i (\bar{\psi_p} O_i \bar{\psi_n})[\bar{\psi_e} O_i (C_i + C_i^{'} \gamma_5)\psi_\nu] + h.c \quad (1)$$

Here $i = S, V, T, A, P$ and $O_i$are the respective operators, while C_i and $C_i^{'}$ are, respectively, the parity-conserving and parity-violating coupling constants for the different interactions. These coupling constants might in general be complex, and invariance under time reversal requires all couplings be relatively real. The SM corresponds to $C_V = C_V^{'} = 1$ and $C_A = C_A^{'}$, all other coupling constants being zero. The pseudoscalar contribution vanishes to lowest order for $\beta-$decay since $O_P = \gamma_5$ couples large to small components of the nuclear wave functions and thus

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the hadronic matrix element with O_P in the above Hamiltonian is very small.

Which of the other interactions actually do occur in Nature, as well as their properties with respect to the $P-$ and $T-$operations, can be investigated by measuring $ft-$values [10, 11] for well-chosen transitions or by measuring different types of correlations between the spin and momentum vectors of the particles involved in $\beta-$decay (i.e. the spin $\mathbf{J}$ of the nucleus, the spin σ and momentum $\mathbf{p_e}$ of the $\beta-$particle and the momentum $\mathbf{p}_\nu$ of the (anti)neutrino). Such experiments yield the so-called correlation coefficients that depend only on the nuclear matrix elements for the observed $\beta-$transition and on the weak-interaction coupling constants.

Jackson *et al* [9] used the Hamiltonian in Eqn. 1 with final-state Coulomb corrections to predict observables. They obtained the decay rate for spin-polarized nuclei which described the distribution in lepton direction, electron polarization, and electron energy (only the terms relevant to this article are included below):

$$\frac{d\Gamma}{dE_e d\Omega_e\, d\Omega_\nu} \propto 1 + a_{\beta\nu}\frac{\mathbf{p_e}\cdot\, \mathbf{p}_\nu}{E_e\, E_\nu} + b_f\frac{m_e}{E_e} + ... \quad (2)$$

The $\beta - \nu$ angular correlation coefficient $a_{\beta\nu}$ in the relation shown above are experimentally determined and depends on the coefficients C_i and $C_i^{'}$. b_f is the Fierz interference term. For pure Fermi (F) transition and pure Gamow-Teller (GT) transitions, this dependence can be approximated as

$$a_{\beta\nu}^{F} \simeq 1 - \frac{|C_S|^2\ +\ |C_S^{'}|^2}{|C_V|^2}\ ,$$

$$a_{\beta\nu}^{GT} \ \simeq\ -\frac{1}{3}\left[1 - \frac{|C_T|^2\ +\ |C_T^{'}|^2}{|C_A|^2}\right]\ . \quad (3)$$

In the SM, *i.e.*, in the absence of S- and T-type interactions, $a_{\beta\nu}^{F} = 1$ and $a_{\beta\nu}^{GT} = -\,0.333$. Any admixture of S to V interaction in such a pure Fermi decay would result in $a_{\beta\nu}^{F} < 1$. The measurement of $a_{\beta\nu}$ therefore yields information about the interactions involved. However,

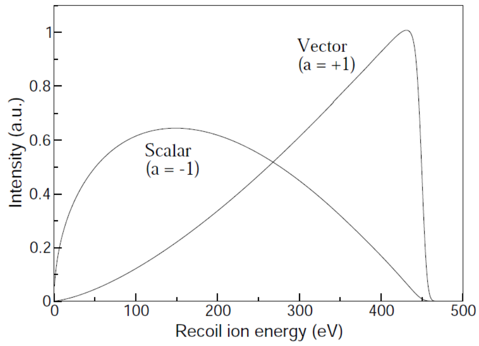

FIG. 1: Differential recoil energy spectrum for a=1 (pure V interaction) and a=-1 (pure S interaction) [12]

the neutrino cannot be detected directly in such an experiment, and the $a_{\beta\nu}$ angular correlation has to be inferred from other observables. From properties of the general Hamiltonian of weak interaction and of the Dirac matrices, it can be shown that V interaction takes place only between a particle and antiparticle with opposite helicities, while in the case of S interaction it takes place only between a particle and antiparticle with the same helicities. Therefore, in superallowed $0^+ - 0^+$ Fermi decay, where β and neutrino spins have to be coupled to zero, a particle and antiparticle will be emitted preferably into the same directions for V interaction and into the opposite directions for S interaction. This will lead to a relatively large energy of the recoil ion for V interaction and a relatively small recoil energy for S interaction (Fig.1)

2. Scientific motivation

The aim of the TAMU-TRAP facility is to improve the limits on $S-$ interactions by measuring $a_{\beta\nu}$ in $0^+ - 0^+$ $(T\ =\ 2)$ $\beta-$delayed proton decays. Eqn. 2 applies to these decays equally well. In case of $\beta-$delayed proton decays, following the $\beta-$decay, the daughter nuclei is in a proton-unbound excited state. This results in a significant probability of a proton being emitted from the daughter nucleus. As mentioned earlier, If the β and ν tend to go off in the same direction (Vector interaction) then

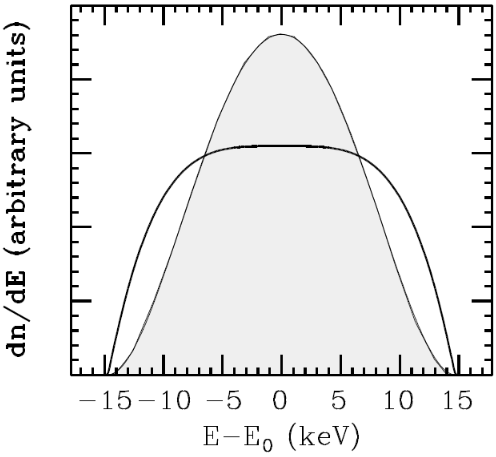

FIG. 2: Intrinsic shapes of the beta delayed proton group from ^{32}Ar $0^+ \rightarrow 0^+$ for Vector (unshaded curve) and Scalar (light-shaded curve) interactions [13]

their momentum can cancel with the result that the daughter nucleus recoils with less energy. The two cases lead to significantly different shapes for the proton energy spectrum. A vector interaction leads to a relatively flat distribution whereas a scalar leads to one peaked at the proton's rest-frame energy. It is in this way that the shape of the Doppler-broadened proton is sensitive to $a_{\beta\nu}$. The energy spectrum for the two types of interactions is shown in Fig.2 [13].

TAMU-TRAP will increase the sensitivity to $a_{\beta\,\nu}$ over the result in Ref. [13] and reduce backgrounds by observing the β and proton in a coincidence measurement. TAMU-TRAP experiment will use a cylindrical Penning trap to store the radioactive ions. The ions will decay at the centre of the trap which will have double-sided Si-strip annular detectors on either side to observe both the protons and the β's. These two particles will be separated by their different Larmor radii and energy signals in the DSSSDs, allowing us to observe cases where the beta was emitted on the same side as the proton as well as the opposite side. The $T = 2$ nuclei are especially interesting because a recent comparison of isospin-mixing corrections by I.Towner [14] indicate a systematic dependence with isospin with the type of model used (either a Woods-Saxon plus Coulomb potential or a Hartree-Fock calculation). To test the calculations and add new cases from which V_{ud} may be extracted requires measurements of the ft value to the sub-percent precision. For $\beta-$delayed proton emitters, this corresponds to measuring the proton and γ branching ratios from the 0^+ state as well as the lifetime, all to sub-percent level. A proof-of-principle measurement on ^{32}Ar has been demonstrated and we plan to refine these measurements with the Penning trap system. The program will continue measuring a number of other $T = 2$ nuclei.

3. TAMU-TRAP facility at T-REX upgrade project

T-REX is the major upgrade project at Texas A & M University. It is described in detail in Ref. [15]. The idea behind T-REX is to re-commission the old 88" K150 cyclotron and couple it to the existing superconducting K500 cyclotron via light ion and heavy-ion guide system. This will open up the possibility to run two RIBs in parallel and can re-accelerate beams of radioactive ions. The Institute carries out a program of basic research and education in both nuclear physics and nuclear chemistry. It encompasses experimental and theoretical work in nuclear structure, nuclear astrophysics, fundamental interactions, nuclear dynamics and atomic physics. Fig.3 shows schematic layout of the present and upgrade (T-REX) facility. Fig.4 describes the part of the upgrade project as related to TAMU-TRAP facility.

Primary beam from the re-commissioned K150 cyclotron will be impinged on the gas target, producing RIB's in inverse kinematics by in-flight method. Reaction product of interest will be separated using a large-bore 7T field superconducting solenoid (BigSol). The high energy radioactive beams with wide energy spread at the exit of the BigSol will be converted into low energy ions using a gas catcher. The low energy radioactive

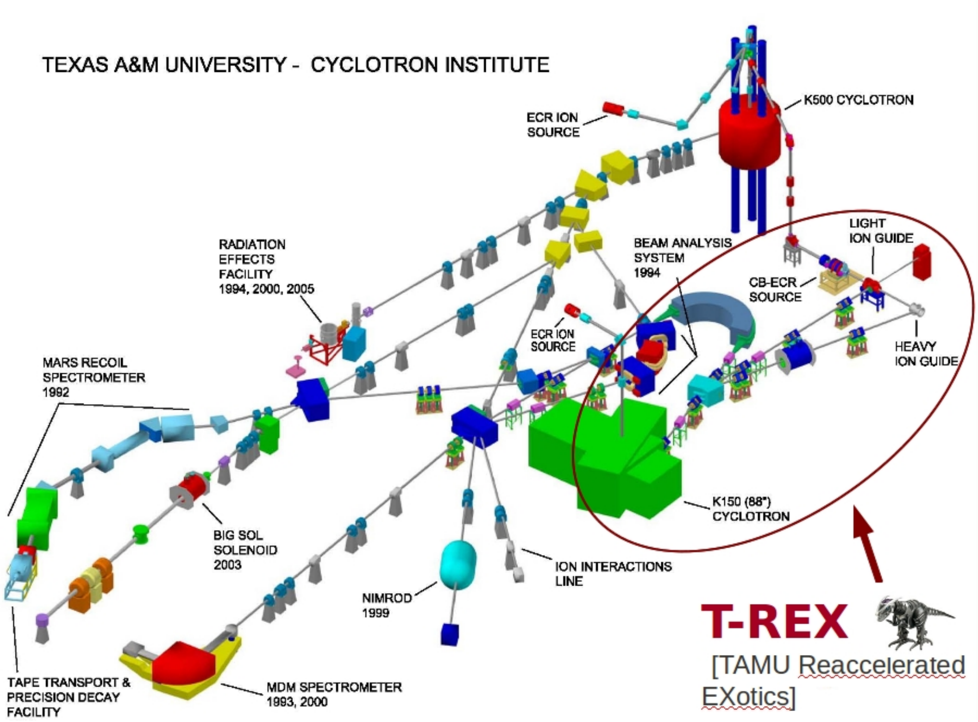

FIG. 3: Layout of Cyclotron Institute research facility.

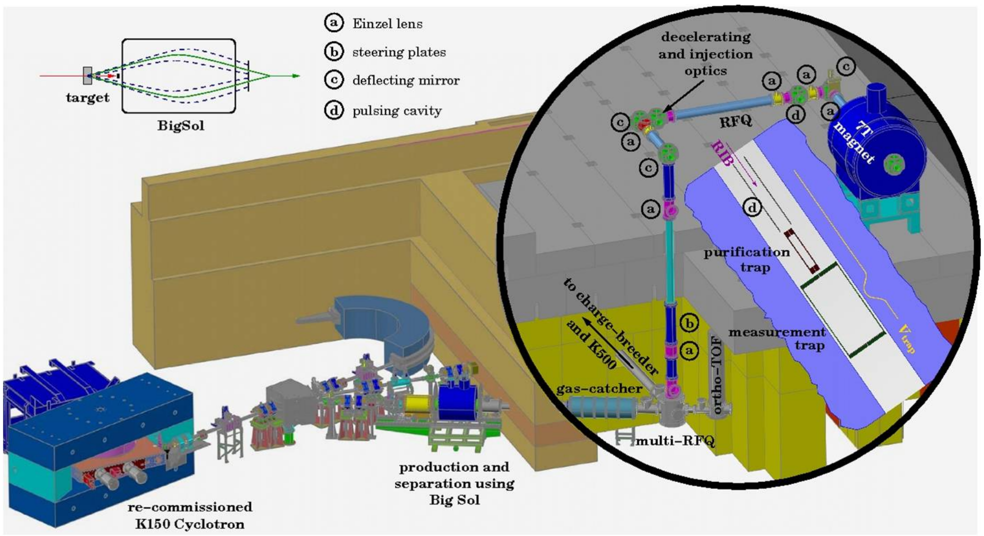

FIG. 4: Layout of TAMU-TRAP facility coupled to T-REX upgrade project

beams will be extracted from the gas catcher with upto 30-40% of efficiency to a switch-yard section (which consists radio frequency quadrupoles). After leaving the switch-yard section the radioactive ion beam will be accelerated upto 10-15 keV and then direct the beam to one of : the ECR charge-breeder and then to the K500 cyclotron for re-acceleration, the ortho-TOF (for diagnosing the extracted beam constituents) or up through the roof plank to TAMU-TRAP facility. The layout of the TAMU-TRAP facility is shown in Fig.4. Simulation of this system have been carried out using SIMION [16]. Beam will be directed with the help of einzel lens and deflector to radio frequency quadrupole (RFQ) for cooling and bunching the ions.

Ions will be cooled and bunched with a gas filled segmented RFQ. The RFQ buncher will be 85 cm long consisting of four rods. The rods are divided longitudinally into 28 segments. The diameter of the rod is 14 mm and the distance between opposite rods is 12 mm (see Fig. 5). The RFQ will be operated at room temperature with $q = 0.5$ and gas (He) pressure typically $1{\times}10^{-2}$ mbar. the longitudinal electric field of 0.1 V/cm is applied to first 25 segments of the system, and ions will be accumulated at the end of the RFQ by forming a deeper potential on the final three segments of the system. It takes less than 600 μs for the ions to accumulate in the potential well and come to equilibrium. Extraction from the RFQ is improved by not only lowering the potential on the last electrode (28^{th} segment), but at the same time increasing the potential on the 26^{th} electrode. This effectively kicks the ions out and minimizes the time spread of the bunched ions. Bunched beam will be further guided using einzel lens and deflector into the Penning trap system which is located in a superconducting magnet that delivers a field of 7 T. Beam entering the Penning trap system will have a spread in time as well as energy. Typically, SIMION calculations for $A = 50\ amu, f = 1\ MHz$ and $V_{pp} = 90\ V$ indicate a time spread on the order of 1.5μs−2.5μ s (FWHM) and an energy spread of 5 eV (FWHM).

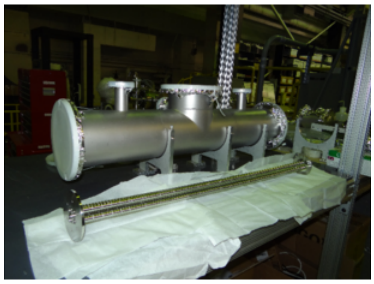

FIG. 5: Photo of the assembled RFQ buncher.

The TAMU-TRAP Penning trap system [17] incorporates two cylindrical Penning traps within a large-bore (210 mm diameter) superconducting solenoidal magnet having a field strength of 7 T. The first trap will be used optionally to further purify the incoming ion beam. The second *measurement* trap employs five electrodes with an inner radius of 90 mm, which will be the largest of any existing Penning trap. The geometry was calculated from first principles. Using electrostatic techniques, an analytic description of a cylindrical, five electrode Penning trap of any electrode dimensions including gaps between electrodes, with endcaps of arbitrary voltage (to approximate detectors) was determined. Expanding the resulting potential at the trap center in Legendre polynomials and identifying the quadrupole term, the geometry was made both tunable and orthogonal. The cross sectional view of the trap design including the resulting field lines is shown in Fig.6.

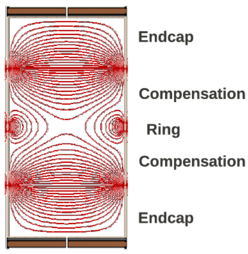

FIG. 6: Cross-sectional view of the measurement trap with field lines [17].

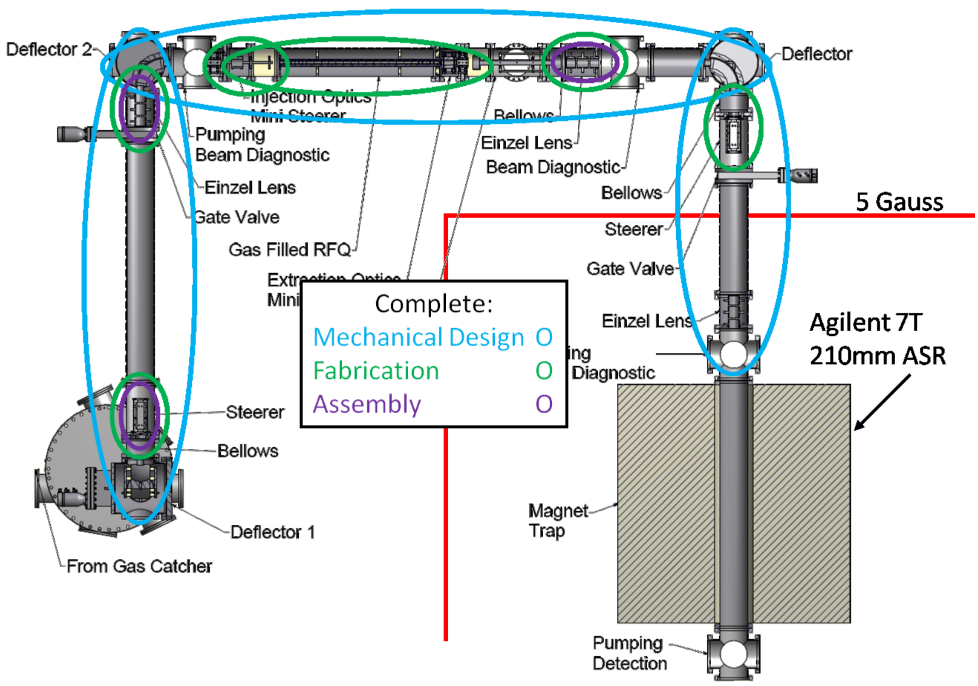

FIG. 7: Current progress towards completion of the TAMU-TRAP facility

4. Current Status of the TAMU-TRAP facility

Fig. 7 shows the current progress of the TAMU-TRAP beam line that has been described. Geometrical optimization in SIMION and mechanical design using Autodesk inventor has been completed for the entire beam line up to the entrance of the Penning trap system. Mechanical drawings have been finalized and submitted to different sources for fabrication, including our in-house machine shop. Fabrication has been completed on several einzel lenses, beam steerer, and all elements composing the RFQ. A custom beam support and mounting table has been designed and installed using extruded aluminum profiles. In addition to beam line hardware, progress has been made on several critical systems. A pressure maintenance controller for the gas filled RFQ has been characterized, and many of the high-voltage electronics have been specified and tested. Electronics for the RFQ have been developed and tested. The immediate outlook for the TAMU-TRAP facility involves continued assembly of the beam line and its constituent elements.

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