TAMU-TRAP: an ion trap facility for Weak Interaction and Nuclear Physics

P.D. Shidling
Cyclotron Institute,
Texas A&M University
Outline of the talk

**Motivation**
- I. Low energy test of Standard Model
- II. Superallowed transitions (T=2)

**T-REX**
- I. T-REX upgrade project
- II. Production & Thermalization of Radioactive Ion Beams

**TAMU-TRAP Facility**
- I. Facility layout
- II. Current Status
$\beta$-$\gamma$ correlation, Fierz interference term.
Measurement of $ft$ value.
Mass measurement, Decay station, Laser spectroscopy...
In Standard Model (SM) weak interaction is $V-A$. 
In Standard Model (SM) weak interaction is $V$-$A$
Motivation

In Standard Model (SM) weak interaction is $V$-$A$.

In general $\beta$ decay can also be Scalar, Tensor, $V$+$A$ interaction.

SM Interaction

Non SM Interaction

Pure Fermi transition
Motivation

In Standard Model (SM) weak interaction is $V$-$A$.

In general $\beta$ decay can also beScalar, Tensor, $V$+$A$ interaction

**Correlation parameter**

$$ W(\theta) \cong \left( 1 + a \beta_\nu \frac{p_e p_\nu}{E_e E_\nu} \cos \theta \right) + b \frac{m_e}{E_e} $$

$\beta$-$\nu$ correlation parameter

Fierz Interference term

$$ \tilde{a} = \frac{a \beta_\nu}{1 + \frac{\Gamma m_e}{E_e} b} $$

Jackson, Treiman and Wyld (Phys Rev 106 and Nucl Phys 4, 1957)
In Standard Model (SM) weak interaction is $V-A$.

In general $\beta$ decay can also be Scalar, Tensor, V+A interaction.

Correlation parameter $W(\theta) \approx 1 + a \frac{p_e p_\nu}{E_e E_\nu} \cos \theta e_\nu + b \frac{m_e}{E_e}$

$\beta-\nu$ correlation parameter

Fierz Interference term

Pure Fermi transition

$\tilde{a} \approx 1$

Test of Standard Model
\[ \mathcal{F}_{t}^{0^+ \rightarrow 0^+} \equiv f_{V} t_{0^+ \rightarrow 0^+} \left( 1 + \delta'_{R} \right) \left( 1 + \delta_{NS}^{V} - \delta_{C}^{V} \right) \]

\[ = \frac{2 G_{F}^{2} V_{ud}^{2} C_{V}^{2} (1 + \Delta_{R}^{V})}{K}. \]

Isospin symmetry breaking correction

- Mixing of states of same spin
- Difference in \( n \) and \( p \) radial wave functions

\[ \delta_{C} = \delta_{c1} + \delta_{c2} \]

- Model dependence \( \delta_{c2} \) seem to depend on \( T \).
$f t$ value measurement

Pure Fermi transition

Radiative corrections

Isospin symmetry breaking correction

Mixing of states of same spin
Difference in $n$ and $p$ radial wave functions

$\delta_C = \delta_{c1} + \delta_{c2}$

Model dependence $\delta_{c2}$ seem to depend on $T$. Needs experimental verification for large corrections
Approach

\( f_t \) value measurement

Pure Fermi transition

Radiative corrections

\[ 0^+, 2 \]

\[ t_{1/2} \]

\[ Q_{EC} \]

\[ 0^+, 2 \]

\[ Q_{EC} \]

\[ t_{1/2} \]

\[ 0^+, 2 \]

\[ BR \]

T = 2 (Superallowed transition)

- Model dependence \( \delta_{c2} \) seem to depend on T.

Needs experimental verification for large corrections

Mixed

Difference in radial wavefunctions

Mixing of states of same spin

Isospin symmetry breaking correction

Pure Fermi transition

\( \mathcal{F}_t^{0^+} \rightarrow F^0 \)

\( T = 2 \) (Superallowed transition)

\( \delta_{c2} \) seems to depend on T.
Large correction is predicted for $T = 2$ transition.

Measurements will allow to test and verify these corrections.

Why $T = 2$?

Large correction is predicted for $T = 2$ transition.

Measurements will allow to test and verify these corrections.

Why $T = 2$?

Large correction is predicted for $T = 2$ transition.

Measurements will allow to test and verify these corrections.

Beta delayed proton decay

$^{40}$Ti $\rightarrow ^{32}$Ar $+ p$, $0^+, 2$

$^{32}$Ar $+ p$ $\rightarrow ^{30}$Si $+ ^{4}$He, $0^+, 2$

$\beta - \nu$ correlation measurements

$^{31}\text{S} + p \rightarrow 0^+, 2 \rightarrow ^{32}\text{Ar}$

$^{32}\text{Cl}$
Proton contain the information about $^{32}\text{Cl}$ recoil (Doppler)

$^{31}\text{S} + \text{p}$

$^{32}\text{Cl}$

$0^+, 2$ $^{32}\text{Ar}$
Proton contain the information about $^{32}\text{Cl}$ recoil (Doppler)

$^{31}\text{S} + p$ → $0^+, 2$ $^{32}\text{Ar}$

$^{32}\text{Cl}$

$\beta^+$, $\nu_e$

Vector

$\beta^-$, $\nu_e$

Scalar

$\nu_e$

$\beta^+$

**β-ν correlation measurements**

Uniform magnetic field

- Beta & Proton in same hemisphere
- Beta & Proton in different hemisphere

Penning traps
- Increase solid angle.
- Increase sensitivity.
- Allows to detect $e$ along with $p$

![Graph showing energy distribution](image-url)
Motivation
   I. Low energy test of Standard Model
   II. Superallowed transitions (T=2)

T-REX
   I. T-REX upgrade project
   II. Production & Thermalization of Radioactive Ion Beams

TAMU-TRAP Facility
   I. Facility layout
   II. Current Status
K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE

T-REX
[TAMU Reaccelerated EXotics]
Re-commissioning the K150(88``) Cyclotron.
T-REX Upgrade project

- **Re-commissioning the K150(88``) Cyclotron.**
- **Construction of Ion guides (light ion guides & Heavy Ion guides).**
T-REX Upgrade project

- **Re-commissioning the K150(88") Cyclotron.**
- **Construction of Ion guides (light ion guides & Heavy Ion guides).**

### Expected 88” beam intensities and energies

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<tr>
<th>Isotope</th>
<th>Energy (MeV/u)</th>
<th>Intensity (pμA)</th>
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<tbody>
<tr>
<td>p</td>
<td>55</td>
<td>27</td>
<td>$^{20}$Ne</td>
<td>28</td>
<td>3.0</td>
</tr>
<tr>
<td>d</td>
<td>35</td>
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</tr>
<tr>
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<tr>
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Facility upgrade white paper
Production of RIB: Light ion guide

- $(p,n)$, $(d,p)$ and $(\alpha,n)$ reaction.
- Light ion induced fission.

Dr. Gabriel Tabacaru
Production of RIB: Heavy ion guide

- **Heavy ion DIC and fragmentation.**
- **Fusion evaporation reaction.**
Production of RIB: Heavy ion guide

- **Heavy ion DIC and fragmentation.**
- **Fusion evaporation reaction.**

Secondary beams for TAMUTRAP facility
Coupling of TREX to TAMUTRAP facility

K150 Cyclotron
Production target
Big Sol Separator
Gas-catcher
multi-RFQ
to TAMUTRAP
Coupling of TREX to TAMUTRAP facility

Gas Catcher

Length: 0.95 m
(Operating He pressure for cooling: 300 - 400 Torr)

Greg Chubaryan & ANL (G. Savard)

K150 Cyclotron

Production target

Big Sol Separator

Gas-catcher

TAMUTRAP

multi-RFQ
Coupling of TREX to TAMUTRAP facility

- Charge Breeder ECR & K500 Cyclotron
- Mid Point Optics Einzel #3
- Beam Exit Einzel #1 & #2
- Extraction RFQ
- Multi RFQ: Central Lift Micro RFQ Launching RFQ Ion Source
- Ortho-TOF
- Gas Catcher
- Diagnostic and Degrader Box

Beam from BIGSOL

HV Platform

K150 Cyclotron

Production target

Big Sol Separator

Gas-catcher

multi-RFQ

TAMUTRAP
Production of RIB for TAMUTRAP

- Target (Solid/gas)
- Axial Blocker
- SOLENOID
- Circular apertures
- Energy degrader
- ANL Gas Catcher
- Beam from K150
- RIB Diagnostics

K150 Beam Diagnostics
Axial blocker allows to select the angular range and to block the on-axis beam.
Axial blocker allows to select the angular range and to block the on-axis beam.

Circular aperture will allow to select range of reaction products.
Production of RIB for TAMUTRAP

Current Status

- BIGSOL now tested and awaiting installation in the K150 vault.
- Gas catcher is built and is currently being tested.
- Simulation of HIG beam line is work in progress.

- Axial blocker allows to select the angular range and to block the on-axis beam.
- Circular aperture will allow to select range of reaction products.
Production of RIB for TAMUTRAP

Useful nuclear reactions

- Fusion-evaporation
- Projectile like fragments
### Production of RIB for TAMUTRAP

#### Useful nuclear reactions
- Fusion-evaporation
- Projectile like fragments

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<tr>
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<td>$^{40}\text{Ti}$</td>
<td>0.2</td>
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<td>$^{36}\text{Ca}$</td>
<td>2.2</td>
<td>6.3</td>
</tr>
<tr>
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<td>3.3</td>
<td>7.3</td>
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<td>$^{28}\text{S}$</td>
<td>4.5</td>
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</tr>
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Production of RIB for TAMUTRAP

Useful nuclear reactions

• Fusion-evaporation
• Projectile like fragments

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Low energy with high intensity
Production of RIB using MARS spectrometer

Momentum Achromat Recoil Spectrometer (MARS)

R.E. Tribble et al. NIMA 285 (1989) 441

\[ ^{32}\text{S}(^3\text{He},3n)^{32}\text{Ar} @ 23 \text{ MeV/u} \]

\[ ^{24}\text{Mg}(^3\text{He},3n)^{24}\text{Si} @ 23 \text{ MeV/u} \]
Fusion evaporation reaction

$^{36}\text{Ar(}^{3}\text{He,4n)}^{32}\text{Ar} @ 23 \text{ MeV/u}$

$N = Z - 3$

$N = Z - 2$

$N = Z - 1$

$N = Z - 4$

Production of RIB using MARS spectrometer

R.E. Tribble et al. NIMA 285 (1989) 441

Momentum Achromat Recoil Spectrometer (MARS)
Production of RIB using MARS spectrometer

R.E. Tribble et al. NIMA 285 (1989) 441

Fusion evaporation reaction:

\[ ^{32}\text{S}(^{3}\text{He}, 3\text{n})^{32}\text{Ar} \ @ 23 \text{ MeV/u} \]

\[ ^{24}\text{Mg}(^{3}\text{He}, 3\text{n})^{24}\text{Si} \ @ 23 \text{ MeV/u} \]

\[ ^{32}\text{Ar} \]

\[ ^{24}\text{Si} \]

N = Z
N = Z-1
N = Z-2
N = Z-3
N = Z-4

24\text{Si}
Production of RIB using MARS spectrometer

Momentum Achromat Recoil Spectrometer (MARS)

R.E. Tribble et al. NIMA 285 (1989) 441

Production rate at the focal plane detector

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Production Rate</th>
<th>Cross Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{32}\text{Ar}$ Production</td>
<td>$6 \text{ ev/µC}$</td>
<td>$7.3 \text{ (µb)}$</td>
</tr>
<tr>
<td>$^{24}\text{Si}$ Production</td>
<td>$14 \text{ ev/µC}$</td>
<td>$15.5 \text{ (µb)}$</td>
</tr>
</tbody>
</table>

Factor of $\sim 2$ in cross section between $^{32}\text{Ar}$ and $^{24}\text{Si}$ is observed in the experiment.
Fusion evaporation reaction

\[ ^{32}\text{S}(^3\text{He},3n)^{32}\text{Ar} @ 23 \text{ MeV/u} \]

\[ ^{24}\text{Mg}(^3\text{He},3n)^{24}\text{Si} @ 23 \text{ MeV/u} \]

Production rate at the focal plane detector

Rate \((^{32}\text{Ar})\) : 6 ev/µC : 7.3 (µb)
Rate \((^{24}\text{Si})\) : 14 ev/µC : 15.5 (µb)

Factor of \(~2\) in cross section between \(^{32}\text{Ar}\) and \(^{24}\text{Si}\) is observed in the experiment.

Cross section Measurement

Beamtime is scheduled for efficiency measurement of MARS Spectrometer.

Beamtime is scheduled in December 2014 for PLF reaction.

(1) \(^{36}\text{Ar} + ^{12}\text{C}\)
(2) \(^{36}\text{Ar} + ^9\text{Be}\)
(3) \(^{36}\text{Ar} + ^{58}\text{Ni}\)
### Estimated production of T=2 superallowed proton emitters from T-REX

<table>
<thead>
<tr>
<th>RIB</th>
<th>Projectile</th>
<th>$t_{1/2}$ [ms]</th>
<th>Target</th>
<th>Beam Energy (MeV/u)</th>
<th>Production Rate (particles/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{40}$Ti</td>
<td>$^{40}$Ca</td>
<td>53</td>
<td>$^{3}$He</td>
<td>17</td>
<td>$\sim 7 \times 10^4$</td>
</tr>
<tr>
<td>$^{36}$Ca</td>
<td>$^{36}$Ar</td>
<td>102</td>
<td>$^{3}$He</td>
<td>20</td>
<td>$\sim 2.5 \times 10^5$</td>
</tr>
<tr>
<td>$^{32}$Ar</td>
<td>$^{32}$S</td>
<td>98</td>
<td>$^{3}$He</td>
<td>20</td>
<td>$\sim 1.4 \times 10^5$</td>
</tr>
<tr>
<td>$^{28}$S</td>
<td>$^{28}$Si</td>
<td>125</td>
<td>$^{3}$He</td>
<td>20</td>
<td>$\sim 1.5 \times 10^5$</td>
</tr>
<tr>
<td>$^{24}$Si</td>
<td>$^{24}$Mg</td>
<td>140</td>
<td>$^{3}$He</td>
<td>20</td>
<td>$\sim 6.5 \times 10^4$</td>
</tr>
<tr>
<td>$^{20}$Mg</td>
<td>$^{20}$Ne</td>
<td>90</td>
<td>$^{3}$He</td>
<td>21</td>
<td>$\sim 1.4 \times 10^5$</td>
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Motivation
  I. Low energy test of Standard Model
  II. Superallowed transitions (T=2)

T-REX
  I. T-REX upgrade project
  II. Production & Thermalization of Radioactive Ion Beams

TAMU-TRAP Facility
  I. Facility layout
  II. Current Status
Beam

10 cm

10 - 2 - 10 - 4 mbar
2 - 10 ms (cooling time)

Buffer gas cooling

V_{RF} \sim 200 \ V_{AC} ; 
\nu = 0.7 - 1.5 \ MHz

E_{(FWHM)} = 5 \ eV
TOF_{(FWHM)} = 1.2 - 1.4 \ \mu s
Buffer gas cooling
$10^{-2}$-$10^{-4}$ mbar
2-10 ms (cooling time)

$r_0 = 6\, \text{mm} ; r = 7\, \text{mm}$

$V_{RF} \sim 200 \, V_{AC} ;$
$f = 0.7 \text{ -} 1.5 \, \text{MHz}$

Efficiency $\approx 25\%$ (continuous mode)
TAMUTRAP Facility

Cooler & Buncher

M. Mehlmann (Ph.D. Thesis)
TAMUTRAP Facility

Deflectors

off-line ion source
cooler & buncher

7T/210mm magnet

Deflectors

Deflectors

Deflectors

Deflectors

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Deflectors
Entrance of the cylindrical deflector

Exit of the cylindrical deflector (after 90° bend)
Entrance of the cylindrical deflector

Exit of the cylindrical deflector (after 90° bend)

-3100V/3840V

MCP station

REU: Robert McFee
TAMU-Penning Trap
<table>
<thead>
<tr>
<th>Nuclide</th>
<th>Lifetime (ms)</th>
<th>Proton Energy (MeV)</th>
<th>Larmour radii (mm)</th>
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<tbody>
<tr>
<td>$^{20}$Mg</td>
<td>137.05</td>
<td>4.28</td>
<td>42.7</td>
</tr>
<tr>
<td>$^{24}$Si</td>
<td>147.15</td>
<td>3.91</td>
<td>40.8</td>
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<tr>
<td>$^{28}$S</td>
<td>180.33</td>
<td>3.70</td>
<td>39.7</td>
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<tr>
<td>$^{32}$Ar</td>
<td>141.38</td>
<td>3.36</td>
<td>37.8</td>
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<tr>
<td>$^{36}$Ca</td>
<td>141.15</td>
<td>2.55</td>
<td>33.0</td>
</tr>
<tr>
<td>$^{40}$Ti</td>
<td>72.13</td>
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</tr>
<tr>
<td>$^{48}$Fe</td>
<td>63.48</td>
<td>1.23</td>
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### TAMU-Penning Trap

#### Cylindrical Penning Trap

![Cylindrical Penning Trap Diagram]

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*M. Mehlman et al. NIMA 712 (2013) 9*
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**M. Mehlman et al. NIMA 712 (2013) 9**

**Radius : 90 mm**

**l/r = 3.72**
### Nuclide and Properties

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**Cylindrical Penning Trap**

- Radius: 90 mm
- $l/r = 3.72$

**Other existing Cylindrical Penning Trap**

- Radius: 90 mm
- $l/r = 11.75$
TAMU-Penning Trap

Cylindrical Penning Trap

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Radius : 90 mm
\( l/r = 3.72 \)

Other existing Cylindrical Penning Trap

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It will be the world’s open geometry Penning trap.

Correlation measurements (β-delayed proton decay).

Electrode structure is tunable and orthogonalized (Mass measurement).

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Emittance station setup is to study the beam emittance after the exit of cylindrical deflector and cooler & buncher.

Characterizing the cooler and buncher using offline ion gun.
Current Status

- Installed and tested
- Built & tested, but not yet installed
- Built, but not yet installed/tested
Measurement of Correlation parameter/Fierz term in β-decay can be used to search for new Physics.

T-REX upgrade project will increase our RIB capabilities and, can reaccelerate the beam of radioactive ions.

TAMUTRAP facility is a unique facility to study β-delayed proton decay:

Measurement of correlation parameter ($\alpha_{\beta\nu}$), Fierz term. ft value measurement, decay station.....

Characterize the cooler and buncher.

GEANT4 simulation of Penning trap.

Rich Physics program at upcoming TAMUTRAP facility.
Funding/Support:
DOE DE-FG02-93ER40773, Early Career ER41747.

TAMU/Cyclotron Institute