β–ν correlations in $^6$He decay using an electrostatic trap
an “In-House” experiment at the WI

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Collaboration between the Nuclear Structure and the molecular and Atomic Physics
groups. Also scientists from the Hebrew University, Soreq NRC center, MPIK –
Heidelberg and LBL

Ph.D. Thesis of Sergey Vaintraub
Tsviki Hirsh

• Good News…
• Bad News…..
A high precision measurement of the $\beta$-$\nu$ correlation coefficient, "$a$", from radioactive decay of $^6\text{He} \rightarrow ^6\text{Li} + e^- + \nu$ in an Electrostatic ion trap

$$H_{\beta}^{^6\text{He}} = \sum_{i=S,P,V,A,T} \overline{(^6\text{Li})\hat{O}_i} (^6\text{He})[\overline{e}\hat{O}_i(C_i + C_i'\gamma_5)\nu_e] + h.c.$$  

$$dW \propto \xi \left( 1 + a_{e\nu} \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + ... \right)$$

$$a_{e\nu} = a_{GT} = -\frac{1}{3}$$

## β Decay 101 - Possible observables in nuclei

\[ \frac{d\Gamma}{dE_\beta d\Omega_\beta d\Omega_\nu} \propto \xi \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + c \left[ \frac{1}{3} \frac{\vec{p}_e \cdot \vec{j}}{E_e E_\nu} - \frac{(\vec{p}_e \cdot \vec{j})(\vec{p}_\nu \cdot \vec{j})}{E_e E_\nu} \right] + \frac{J(J+1) - 3 \langle \vec{j} \cdot \vec{j} \rangle}{J(2J-1)} \right\} + \frac{\langle \vec{j} \rangle}{J} \cdot \left[ A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right] \]

### Parameters and Observables

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Observable</th>
<th>Sensitivity</th>
<th>SM Prediction</th>
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</table>
| a         | β-ν (recoil) correlation | Tensor & Scalar terms | 1 for pure fermi
|           |            |             | -1/3 for pure GT or combination |
| b         | Comparison of β⁺ to EC rate | SV/T/A interference | 0 |
| (Fierz term) |            |             |               |
| A         | β asymmetry for polarized nuclei | Tensor. ST/VA Parity | Nucleus dependent |
| B         | ν asymmetry (recoil) for polarized nuclei | Tensor, TA/ST/VA/SA/VT Parity | Nucleus dependent |
| D         | Triple product | ST/VA Interference TRI | 0 |
Example: $^6$He beta decay
See, e.g., Flechard et al, PRL (2008)

- New physics beyond the Standard Model’s V–A structure
  “LHC–type” physics at the low energy frontier!

$^6$Li daughter nucleus

$^6$He $\rightarrow ^6$Li + $e^-$ + $\bar{\nu}_e$

$dW \propto a^2 \left( \frac{p_e}{E_e} \cos \theta \right)$

$dW_{SM}(^6$He) $\propto -\frac{1}{3} \left( \frac{p_e}{E_e} \cos \theta \right)$

$\theta$

$e^-$ Electron

$\bar{\nu}_e$ Electron anti-neutrino

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The Standard Model of Particles and Forces

BUT…
Also “Physics Beyond the Standard Model”
Why RNB’s in Traps?

- No possibility for detection of neutrinos
- Small effects - low energy of ions, multiple scattering, angle resolution
- “Single” Atom/Ion in a trap

**World-wide activity** (MOT, Penning, Paul)
- Berkeley
- TRIUMF
- GANIL
- ISOLDE
- Argonne
- Seattle
- WI (commissioning) – **Electrostatic Trap**
- Jerusalem - MOT (initialization phase)
## Beta Decay Studies Worldwide

(Partial List)

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Technique</th>
<th>Group</th>
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<tbody>
<tr>
<td>$^6\text{He}$</td>
<td>Electrostatic Trap</td>
<td>WI (Hass) + HUJI (Ron) + LBL (Kolomensky)</td>
</tr>
<tr>
<td>$^6\text{He}$</td>
<td>MOT</td>
<td>ANL (Mueller) + UW (Garcia)</td>
</tr>
<tr>
<td>$^8\text{Li}$</td>
<td>Paul Trap</td>
<td>ANL (Savard)</td>
</tr>
<tr>
<td>$^{38m}\text{K} / ^{87}\text{Rb}$</td>
<td>MOT</td>
<td>TRIUMF (Behr)</td>
</tr>
<tr>
<td>$^{17\text{25}}\text{Ne}$</td>
<td>MOT</td>
<td>HUJI (Ron)</td>
</tr>
<tr>
<td>$^{26\text{m}}\text{Al} / ^{35}\text{Ar} / ^{46}\text{V}$</td>
<td>Penning Trap</td>
<td>Leuven / WITCH (Severijns)</td>
</tr>
<tr>
<td>$^6\text{He} / ^{35}\text{Ar}$</td>
<td>Paul Trap</td>
<td>LPC CAEN (Fléchard)</td>
</tr>
<tr>
<td>neutron</td>
<td>Many</td>
<td>Many</td>
</tr>
<tr>
<td>$^{21}\text{Na}$</td>
<td>MOT</td>
<td>LBL (Freedman - deceased)</td>
</tr>
<tr>
<td>$^{16}\text{N}$</td>
<td>Electrostatic Trap</td>
<td>WI (Hass)</td>
</tr>
<tr>
<td>$^{21}\text{Na}$</td>
<td>MOT</td>
<td>KVI (Jungmann)</td>
</tr>
</tbody>
</table>
Optical resonator

Particle resonator

Trapping of fast ion beams using electrostatic field

\[ E_k = \frac{qV}{E_k/q} \]
Fig. 2 A schematic view of the EST for β-decay studies. The radioactive ion, like ⁶He, moves with $E_k \sim 4.2$ keV between the reflecting electrodes. The β electrons are detected in position sensitive counters while the recoiling ions, due to kinematic focusing, are detected with very high efficiency in either one (determined by the instantaneous direction) of the annular MCP counters.

Apparent advantages:
• Large solid angles (for BOTH ion recoil and electrons
• Field-free and “equipment-free” inner region
• Simplicity, portability
• Complementary to other method (different systematic errors)
• Full reconstruction of event-by-event - actually measure $\cos(\theta)$!
Ideal Case

\[ dW \propto a \xi \left( \frac{p_e}{E_e} \cos \theta \right) \]

\[ dW_{SM}(^6He) \propto -\frac{1}{3} \left( \frac{p_e}{E_e} \cos \theta \right) \]
Some of the $^6\text{Li}$ ions will miss the MCP at its periphery
Some of the $^6$Li ions will go through the MCP hole.
Sensitivity of measurement to various parameters

"Sensitivity" = \[ \sum [(a=1/3) - (a=-1/3)]^2 \]
Expected Yields for a BeO target:
$^9\text{Be}(n,\alpha)^6\text{He}$
SARAF (40 MeV, 2 mA): $8 \cdot 10^{12}$/sec
SPIRAL2 (40 MeV, 5 mA): $2 \cdot 10^{13}$/sec

Expected Yields for a BN target:
$^{11}\text{B}(n,\alpha)^8\text{Li}$
SARAF (40 MeV, 2 mA): $2 \cdot 10^{12}$/sec

Or,
- from a d+t, 14 MeV n generator
- from d beam - VDG

6He production at ISOLDE (CERN)

Similar possibilities
With ¹¹B(n,α)⁸Li
LiFTiT & 3 MV VDG

Figure 3.20: Unfolded spectrum of LiFTiT by using MCUNED (left) and Liquid Scintillator (right) initial guess spectra.
SARAF Phase I

@ Soreq Center - Israel

- Commissioning of Phase-I is approaching finalization
- 1 mA CW proton beam has been accelerated up to an energy of 3.7 MeV
- Low duty cycle (~0.2 mA) deuteron beam has been accelerated up to an energy of 4.3 MeV
- Phase-II - up to 40 MeV (2015)
A) High energy (14 MeV) neutrons from a d+t NG hit a hot BeO target; $^6$He nuclei are produced.
B) $^6$He atoms are transferred to an EBIT where they get ionized, accumulated, and bunched and guided.
C) The ion bunch is injected into the EIBT for beta-decay studies.
D) Data acquisition: signals from detectors are processed, recorded, and analyzed.
“In-House” Research!
R&D steps at the WI

Use infrastructure (Shielding, radiation protection, equipment) from de-commissioned 14 MV Koffler accelerator
Trapping and bunching of stable $^4$He$^+$ and $^4$He$^{++}$. As expected, the trapping time of $^4$He$^{++}$ is shorter than that of $^4$He$^+$.

- Bunching R&D with $^4$He
- Algorithm and tests of a position-sensitive e-detector
- R&D into specialized design of Electron Beam Ion source
Experimental tests and control of systematic errors

• Using stable 4He that undergo collisions in the residual gas to test the acceptance of the MCP. In particular, this will allow probing any position-dependent efficiency variation of the MCP and possible “edge detection effects” of the MCP on its periphery and around its annular hole.

• Varying trapping voltages (hence, kinetic energy of 6He ions and resulting 6Li recoils) and/or 6He charge state (singly or doubly ionized).

• Varying the bunch length arrangement with respect to the two identical MCP detectors at both ends.

• Using various cuts in the analysis such as those of the electron energy and decay position in the trap.

• Using different strategies of analysis, from event-by-event reconstruction of the angle to the use of distributions such as the 6Li time of flight and position distribution on the MCP’s.
Full $E_\text{e}$ determination + position information

Thick plastic scintillator

Individual photomultipliers
Detector – BC-408

- 65 cm radius circular Plastic Scintillator
- Cover – VIKUITI (3M) >99% Reflectivity
- 7 PMT 1.9 cm Radius
- Scintillation Parameters
  - $\lambda_{\text{max}} = 425 \text{ nm}$
  - $l_{\text{abs}} = 210 \text{ cm}$

$\approx 11000 \ #\text{Ph/MeV}$
Geant4 Simulation

- Dividing area of Detector to squares
- Distribution of Photons in PMTs per square
- Statistical Map
Comparison - Error

Errors Distributions (45° & 90°)

Average error
3.6±2.5

Average error
4.6±2.9
The case of $^{16}\text{N}$

$^{16}\text{N}$ is produced simultaneously with $^6\text{He}$, and with a comparable yield, in the BeO target.

Theoretical work on the $\beta$–$\nu$ correlation coefficient for the forbidden $2^- \rightarrow 0^+$ transition. DG

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Summary

• A novel application of the electrostatic trap concept
• Potential for a significant contribution to the $\beta-\nu$ correlation field
• Experiment “almost” ready to start taking data
• “The proof of the pudding is in the eating….
Many thanks to all my colleagues