The Proton Spectrum in Neutron Beta Decay: First Results with the aSPECT Spectrometer

Werner Heil
University of Mainz/Germany

The aSPECT collaboration:
• Institut für Physik, Universität Mainz, Germany:
• Institut für Kernchemie, Universität Mainz, Germany:
  K. Eberhardt
• Physik-Department E18, TU München, Germany:
• Forschungsneutronenquelle Heinz-Maier-Leibnitz, Garching, Germany:
  D. Rich
The Decay Probability

Jackson et al., PR 106, 517 (1957):

\[
dW \propto \rho(E_e) \cdot \left\{ 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} \right. \\
+ \left. \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} + \ldots + R \frac{\vec{p}_e \times \vec{\sigma}_e}{E_e} \right) \cdot \vec{\sigma}_n \right\}
\]

Beta-Asymmetry \( A = -2 \frac{|\lambda|^2 + \text{Re} \lambda}{1 + 3|\lambda|^2} \)

Neutrino-Electron-Correlation \( a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \)

Neutron lifetime \( \tau_n^{-1} = \int \rho(E_e) \propto G_F^2 V_{ud}^2 \left( 1 + 3|\lambda|^2 \right) \)
CKM-Matrix Unitarity Test

Cabbibo-Kobayashi-Maskawa-Matrix

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{td} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

Unitarity Condition

\[|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1\]

- Superallowed Fermi Decays
- Free Neutron Decay
- Pion Decay

\[\tau^{-1}_\beta \propto G_F^2 V_{ud}^2 \left(1 + 3|\lambda|^2\right)\]

- Beta Asymmetry \(A(\lambda)\)

\[A = -2 \frac{|\lambda|^2 + \text{Re} \lambda}{1 + 3|\lambda|^2}\]

- Neutrino-Electron-Correlation \(a(\lambda)\)

\[a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2}\]
New $V_{us}$ Measurements

Summary: Blucher et al, hep-ph/0512039

- $f_+(0) \sqrt{1 - |V_{ub}|^2 - |V_{ud}|^2}$
- $K^+_{e3}$ [PDG 2002]
- $K^+_{e3}$ [new]
- $K_L e_3$ [PDG 2002]
- $K_L e_3$ [new]
- $K_L \mu_3$ [new]
- $K_S e_3$ [new]
• Neutron Lifetime Discrepancy needs to be solved. \( \tau_n^{-1} \propto G_F^2 \cdot (1 - |V_{us}|^2 - |V_{ub}|^2) \cdot (1 + 3|\lambda|^2) \)

• A measurement of \( a \) is independent of possible unknown errors in \( A \), systematics are entirely different.

• Present experiments have \( \Delta a/a \sim 5\% \), our aim is \( \Delta a/a \sim 0.3\% \)
The Neutrino Electron Correlation and the Proton Spectrum in Neutron Decay

The correlation coefficient $a$

$$d\omega \propto \left( 1 + a \frac{\nu}{c} \cos(p_e, p_{\bar{\nu}_e}) \right)$$

Sensitivity of the Proton Spectrum to $a$:

Proton kinetic energy is big

Proton kinetic energy is small

preferred $a > 0$

$a < 0$
Ratio \(|g_A/g_V|\) derived from the proton spectrum in free-neutron decay

Chr. Stratowa, R. Dobrozemsky, and P. Weinzierl

Physics Institute, Research Center Seibersdorf, Österreichische Studiengesellschaft für Atomenergie m.b.H., Lenaugasse 10, A-1082 Vienna, Austria

(Received 11 July 1978)

\[ \approx 2 \text{ p/s} \]
\[ \approx 90 \text{ p/s} \]
\[ 7.5 \times 10^5 \text{ p/cm}^2/\text{s} \]

\[ a = -0.1017 \pm 0.0051 \]

uncertainty dominated by systematics:

- p-detector energy calibration
- corrections for thermal n-motions
- p-scattering from residual gas
- ...

\[ \left( \frac{W(E)_{a=0.1}}{W(E)_{a=0}} - 1 \right) \cdot 100\% \]
New efforts to remeasure the \( a \)-coefficient:

  
  \( a \) derived from a measurement of the integral spectrum of recoil protons stored in a quasi-Penning trap.

  \[
  a = -0.1054 \pm 0.0055
  \]

- \( \text{aSPECT} \) (O. Zimmer et al., NIM A440 (2000) 548)
  
  electromagnetic recoil proton spectrometer similar to Byrne et al., designed to correct some of its weaknesses, i.e.,

  - incomplete transfer of energy from transverse to longitudinal motion
  - violation of adiabatic conditions
  - ....

- \( \text{aCORN} \) (F.E.Wietfeldt, Mod.Phys. Lett. A20 (2005) 1783)
  
  relies on coincidence detection of \( \beta \)-electron and recoil proton
Principle of a Retardation Spectrometer

MAC-E-Filter

Magnetic Adiabatic Collimation and Electrostatic Filter

- transverse energy in cyclotron motion $E_\perp$ adiabatically reduced into longitudinal energy $E_\parallel$ along $B$
  \[ \mu = \frac{E_\perp}{B} = \text{const}. \]
- retardation of $E_\parallel$ by electrostatic filter potential (+V)

- spectrometer accepts full solid angle (4π)
- transmission function of spectrometer well known
Principle of a Retardation Spectrometer

Transmission function $T_U(E)$ in the adiabatic limit:

$$T_U(E) = \begin{cases} 
0 & ; \quad E < eU \\
1 - \sqrt{1 - \frac{B_0}{B_A} \left(1 - \frac{eU}{E}\right)} & ; \quad \text{otherwise} \\
1 & ; \quad E > eU/(1 - B_A/B_0)
\end{cases}$$
The \textit{\textalpha SPECT} spectrometer

- Electric Potential (Volt): 0 to 800V
- Magnetic Field (Tesla): $B_0=3T$, $B_A=0.6T$, $B=6T$
- Detector: -30kV
- Neutron Beam: 0 V
- Mirror Electrode: 1 kV

Diagram showing the analysis plane with specific voltages and magnetic fields.
Setup @ MEPHISTO

- Beam Line
- Neutrons
- Beam Stop
- SPECT - SPECTROMETER
- Analyzing Plane 0 to 800 V
- Detector
- Protons
- Neutrons
- Decay volume
- Beam Line
The Proton Detector

Segmented Si - PIN - Diode
- Active Area $25 \times 25 \text{ mm}^2$
- Segmented in 25 Stripes
- Thin Entrance Window
  - Dead Layer: 67 nm
  - Energy Loss for 30 keV protons: $\sim 8$ keV

$\Rightarrow$ talk of Martin Simson
Typical Proton Event

Proton Pulse Shape

Pulse Height $\propto$ Energy

Event Length: about 2 $\mu$s
• Proton spectrum looks ok, Count rate ~ 500 Hz
• Signal to background ratio > 10:1
• Proton Signal not well separated from electronic noise
Extraction of $a$

- statistical accuracy: $\Delta a/a = 13\%$ in nearly 1 h of data taking time
  $\Rightarrow \approx 60-70 \text{ days for } \Delta a/a = 0.3\%$
- measured “$a$” : $-0.106 \pm 0.007 @ January 2006$ - run
but ….

\begin{align*}
a &= -0.174 \pm 0.011 \ldots @ April 25,'06 \\
a &= -0.191 \pm 0.009 @ April 26,'06 \\
a &= -0.130 \pm 0.010 @ April 27,'06
\end{align*}

In the analysis we have to assume that background rate does not depend on analyzing plane voltage.

\[
N_{BG}(U) = N_{BG}(780V)
\]

\[
N_{proton}(U) = N(U) - N_{BG}(780V)
\]
U = 780 V
aSPECT spectrometer setup has topological similarity to the classical Penning trap

\[
R(H_2^+)=\sigma_{ion}(U) \cdot (2.7 \times 10^{16} \cdot P_{H_2}[\text{mbar}]) \cdot l[\text{cm}] \cdot (n_{e^-}/s)
\]

\[\text{e}^- \text{ on } H_2\]
Improvements for the next beam time at ILL
Nov. 2007 – Febr. 2008

Penning discharge

- reduced field-emission
  good surface conditions (electropolishing, mechanical polishing )

- re-design of electrode system between analyzing plane and detector
  ( in particular E×B – electrode)

- since \( R(H_2) \propto p_{H_2} \) vacuum improved by SAES getters

- reduced HV ( \approx \text{factor } 2 \) \( \Rightarrow \) silicon drift detector
- Strict separation of proton peak and electronic noise
- Lower proton energy → lower detector-HV sufficient
Transmission function $T_U(E)$ in the adiabatic limit:

$$T_U(E) = \begin{cases} 
0 & ; \quad E < eU \\
1 - \sqrt{1 - \frac{B_0}{B_A}(1 - eU/E)} & ; \quad \text{otherwise} \\
1 & ; \quad E > eU/(1 - B_A/B_0)
\end{cases}$$

For $\delta a = 3 \cdot 10^{-4}$:

$$\delta (B_A/B_0) \approx 10^{-4}$$

$$\delta U \approx 10 \text{ meV}$$

- Online-monitoring of $B_A/B_0$ with 2 static NMR-probes
- Electric potential measurements: accurate voltage measurement with multimeter, but: surface charges

Kelvin probe:
- Tool to measure work functions

$$V_{Bias} = -V_C$$

$$dQ/dt = 0$$
Kelvin Probe: First results

In collaboration with Prof. I. Baikie, KP Technologies
Design of an Antimagnetic Screen

Influence on the Internal Magnetic Field:
• influence quite small
• the value of $B_0/B_A$ changes
  $\Rightarrow$ online-monitoring of $B_0/B_A$

Influence on the External Magnetic Field:
Calibration Source, Concept 1: Electron Impact He\(^+\) / p-Source

Monoenergetic calibration source:
Aim: \(\Delta E \sim 10 \text{ meV}\)
The neutron decay spectrometer aSPECT finished its first data taking period at FRM II.

Expected rates of decay protons ($\approx 500 \text{ Hz}$)

Data analysis shows that “proton”-background caused by Penning discharge cannot be subtracted in a definite manner.

Brute force measures: field-emission↓, vacuum↓, high-voltage↓, re-design of electrode system.

Further improvements (new proton detector, calibration source, anti-magnetic Screen, on-line NMR probe, Kelvin probe).

Influence on the Internal Magnetic Field

- Decay Volume

**Magnetic flux density** \( B_{on-axis} \) [T] vs. **Position** \( z \) [m]

- Analyzing Plane

**Magnetic flux density** \( B_{on-axis} \) [T] vs. **Position** \( z \) [m]

**Planned:**

Online-monitoring of \( B_0/B_A \) with a movable internal hall probe.
New Neutron lifetime measurement

Fermi-Transition: \( g_V = G_F \cdot V_{ud} \)
Gamow-Teller-Transition: \( g_A = G_F \cdot V_{ud} \cdot \lambda \)

\[ |V_{ud}| = \sqrt{1 - |V_{us}|^2 + |V_{ub}|^2} \]

Neutron Measurements needed:
- Neutron lifetime \( \tau_n \)
  \[ \tau_n^{-1} \propto G_F^2 V_{ud}^2 \left( 1 + 3|\lambda|^2 \right) ; \lambda = g_A/g_V \]
- Beta Asymmetry \( A(\lambda) \)
  \[ A = -2 \frac{|\lambda|^2 + \text{Re} \lambda}{1 + 3|\lambda|^2} \]
- Neutrino-Electron-Correlation \( a(\lambda) \)
  \[ a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} \]
Residual Gas Influence - Calculations

Monte Carlo calculations by F. Glück:
- Using theoretical cross sections for p-H\textsubscript{2}-collisions on microscopic scale
- Limits for all three processes for influences to $a$ at a level of $\delta a \sim 10^{-4}$ (critical pressure $p_{cr}$):

A) Elastic Scattering; for p-H\textsubscript{2}-collisions:

<table>
<thead>
<tr>
<th>$U_8$ [kV]</th>
<th>$p_{cr}$ [mbar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3</td>
<td>$5 \times 10^{-8}$</td>
</tr>
<tr>
<td>-0.3</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>-0.03</td>
<td>$1.4 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

B) Inelastic Scattering; Vibrational excitations in p-H\textsubscript{2}-collisions: $p_{cr} = 4 \times 10^{-8}$ mbar

C) Charge exchange processes: Calculated for different residual gas types:

<table>
<thead>
<tr>
<th>Gas</th>
<th>$p_{cr}$ [mbar]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ar</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>H\textsubscript{2}, Ne</td>
<td>$2 \times 10^{-8}$</td>
</tr>
<tr>
<td>O\textsubscript{2}</td>
<td>$4 \times 10^{-8}$</td>
</tr>
<tr>
<td>He</td>
<td>$10^{-6}$</td>
</tr>
</tbody>
</table>
Background subtraction:
• Measurement at Analyzing Plane Voltage $U$: electrons, protons, gammas
• Measurement at Analyzing Plane Voltage 780 V: electrons, gammas
• Difference: protons

Problem: Correlated Background

- Detector Dead time $\sim 5 \mu$s (TOF(proton) $> 6 \mu$s)
- $e^-$ and $p$ in correlated background events distinguishable
Concept of Monoenergetic Helium Ion Source

Monoenergetic calibration source:
Aim: $\Delta E \sim 10$ meV

$^4\text{He}$

- To the spectrometer

Top view:

$\text{BaO-Cathode}$

$\text{He}^+$

$\text{e}^-$

$-1000\text{V}$

$-400\text{V}$

$-500\text{V}$

$-10\text{V}$

$B$
aSPECT, Collimation System

Lead shielding
Boron polyethylene shielding
Lithium Fluoride shielding
Determination of the Coupling Constants

Fermi-Decay:
\[ g_V = G_F \cdot V_{ud} \]

Gamow-Teller-Decay:
\[ g_A = G_F \cdot V_{ud} \cdot \lambda \]

Two unknown parameters, \( g_A \) and \( g_V \), need to be determined in 2 experiments

1. Neutron-Lifetime:
\[ \tau_n^{-1} \propto \left( g_V^2 + 3g_A^2 \right) \quad \tau_n \approx 885 \text{ s} \]

2. Beta-Asymmetry:
\[ A = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \approx -0.1 \quad \lambda = \frac{g_A}{g_V} \]
Overview of the αSPECT spectrometer

Coefficient $a$: angular correlation between electron and antineutrino

\[ dW \propto 1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \ldots \]

Our aim: $\delta a \approx 3 \cdot 10^{-4}$

Two extreme cases:

- Preferred: $a > 0$
- Preferred: $a < 0$

Decay rate $w(E)$

Spectrum for $a = 0$
Spectrum for $a = 1$

Proton kinetic energy $E$ [eV]