Towards a measurement of the beta energy spectrum in $^6$He decay

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Scope and Outline

• Review the motivations for measurements of the shape of the beta particle energy spectrum in GT transitions.

• Discuss new techniques using implanted $^6$He ions inside active detectors.

1. Motivations
2. Previous measurements in $^6$He
3. Experimental difficulties
4. An experiment using fragmented radioactive beams
5. Data analysis and simulations
6. Summary and Outlook
Motivation: $\alpha$ in $^6\text{He}$ decay

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Experiments require an accurate description of beta spectrum within SM.
**Motivation: \( b \) in \(^6\text{He} \) decay**

- Sensitivity of searches for NP

Constraints from weak decays


\[
P_F/P_{GT} \quad |b_n|<0.001
\]

\[
\text{Re}(\epsilon_T) \quad \text{Re}(\epsilon_S)
\]

\[
b_0 = -0.0022 \pm 0.0043
\]

- Competitive limits as compared with projected LHC, requires a precision level \( \Delta b < 10^{-3} \).
Motivation: WM in $^6$He decay

- The contribution of the weak magnetism form factor to the linear term of the shape factor in the beta energy spectrum is estimated to produce a slope $+0.66 \%$/MeV$^1$.

- This corresponds to the average slope (with opposite sign) of a Fierz term for $b \sim 0.05$.

- Any attempt to reach $\Delta b < 0.05$ should then first see the effect of IWC, if strong CVC holds.

(1) F. Calaprice and B.R. Holstein, NPA 273 (1976) 301
2. Previous measurements in $^6$He
Previous measurements of beta spectrum

The only "publication"

The Beta-Spectrum of He$^8$

C. S. Wu, B. M. Rustad, V. Perez-Mendez, and L. Lidofsky
Columbia University, New York, New York
(Received August 5, 1952)

Magnetic spectrometer; extract end-point energy

B.M. Rustad and S.L. Ruby, PR 97 (1955) 991

Plastic scintillator (control spectrum); conclude weak interaction is dominated by Tensor

Some citations of Schwarzschild's thesis


- Schwarzschild thesis (unpublished) has been cited several times to set some early constraints on exotic couplings but the document is now hard/impossible to find...
3. Experimental difficulties
Some known instrumental difficulties

- Any partial energy deposition in the detector will result in distortions of the energy spectrum.

- Backscattering effects increase at lower energies.
General principle (calorimetry)

A textbook setup to measure the spectrum shape

- Well localized and clean source
- $4\pi$ solid angle and 100% detection efficiency
- Detection of $\beta$ particles without backscattering, out-scattering, or energy loss in dead-layers.

How close can we get to such conditions with radioactive implanted ions produced by fragmentation?
4. Experiment using fragmented radioactive beams
**Implementation and questions**

1. Are the "cocktail beams" produced by fragmentation sufficiently pure for such a measurement? LISE++ separation calculation OK, but not reliable below $10^{-2}$ level.

2. What are the ion induced backgrounds in detectors during implantation? R. Ronningen: PHITS Radiation transport calculation for implantation in CsI(Na), NaI(Tl), Ge, CH$_2$ and follow decays products: OK. To what level is this reliable?

3. Can the implanted ions produce damages in the detectors (light output changes)? Many studies for doses $10^{13}$ or larger but no sensitivities for “low” doses $10^7$-$10^8$. 

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Ions produced by fragmentation $\rightarrow$ Active detector $\rightarrow$ Range of $\beta$ particles
NSCL Coupled Cyclotron Facility

Primary beam: $^{18}$O
150 MeV/A

Production target (Be)

Wedge (Al)

Extraction: $1.2 \times 10^5$ $^6$He/s

- $\Delta p/p = 1\%$
- $\Delta x \times \Delta y = 1.5 \times 2 \text{ mm}^2$

- No traces of $^8$Li or $^9$Li contamination
**Experimental setup**

- Implant $^6$He ions "deep enough" in the detector.
- The range of 3.5 MeV electrons in CsI is 6 mm.
- Requires 40-50 MeV/A ions

- CsI(Na) (2"×2"×5")
- NaI(Tl) (Ø3"×3")
- 2 small CsI(Na) and NaI(Tl) detectors (Ø1"×1")
- 46 MeV/nucleon after degrader
Beam purity and slowing down

Beam energy at implantation detector
(operating the detector at lower gain)

- No traces of $^8$Li or $^9$Li.
- Tail is due to induced reactions in the detector

Vary degrader thickness by rotation

Range distribution in Al degrader
Beam spot size and implantation depth

Transverse dimension

Spot image with high intensity pilot beam on "viewer"

Rectangle: 5x4 mm²

Longitudinal dimension

Deduced implantation depth profile in CsI (LISE++/SRIM) vs degrader angle.
Diffusion of He in solids

- Data of $^6$He in graphite is available (SPIRAL1 target at GANIL) but extrapolation to lower temperatures is questionable.

- Diffusion coefficients of $^4$He:

<table>
<thead>
<tr>
<th>Material</th>
<th>Diffusion coeff. (cm$^2$/s)</th>
<th>Temp. (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>$2.4-5.5 \times 10^{-10}$</td>
<td>293</td>
</tr>
<tr>
<td>NaCl</td>
<td>$2.8 \times 10^{-13}$</td>
<td>369</td>
</tr>
<tr>
<td>Glass</td>
<td>$4.4 \times 10^{-8}$</td>
<td>356</td>
</tr>
</tbody>
</table>

Within ~10 sec, the source “radius” would have increased by at most 10 $\mu$m.
Measuring sequence

Implantation

2.5 s

10-15 s

Decay

(Consistent with $^6$He half-life and a single decay component)
5. *Data analysis and simulations*
Theoretical corrections to beta spectrum

$Z\alpha^2$
(Sirlin'87, not negligible)

$Z^2\alpha^3$
(could safely be neglected)

Radiative correction order $\alpha$, Sirlin'67

Finite size correction, $(L_0 - 1) \times 10^4$
MC simulations

Calculate spectrum of the energy absorbed in the detector, including the effect of escaping bremsstrahlung radiation.

- G4 EM packages
  - Standard
  - Livermore
  - Penelope

- EGSnrc
  - Imp-0
  - Imp-1

- So far, the differences in the comparison between codes/packages/implementations have been observed to be $< 5 \times 10^{-4}$ /MeV.
Background subtraction

Different time windows offer independent analysis with different S/B ratios.

IN SINGLES !!!
Statistics and sensitivity

- 1 h run \( \approx 2 \times 10^6 \) net events
- \( \sim 20 \) runs with CsI(Na) [1 day]
- \( \sim 20 \) runs with NaI(Tl) [1 day]

- Collected about \( 10^8 \) events

Sensitivity

\[ \Delta b \ (\%o) \]

Statistics is not a problem!
**Instrumental effects**

Compare results obtained from two independent measurement using different implantation detectors.

<table>
<thead>
<tr>
<th>Property</th>
<th>NaI(Tl)</th>
<th>CsI(Na)</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal decay time</td>
<td>230 ns</td>
<td>630 ns</td>
<td>Pile-up</td>
</tr>
<tr>
<td>Average Z</td>
<td>32</td>
<td>54</td>
<td>Bremsstrahlung</td>
</tr>
<tr>
<td>Composition</td>
<td>Na, I</td>
<td>Cs, I</td>
<td>Induced reactions</td>
</tr>
</tbody>
</table>

...analysis in progress
Summary...

• Hadronic contributions (WM) should manifest on the way to a precision measurement of $b$, at the level of about $b=0.05$. This provides a sensitive test of any technique for a measurement of $b$ with higher sensitivity.

• We have explored a technique using implanted ions from fragmentation reactions at NSCL and have performed a high statistics measurement of the $^6$He beta energy spectrum.

• No optimization has been made so far (detector size-ambient background-bremsstrahlung-external shield…). The first shot indicates that beam induced activation is ~3 times smaller than ambient background.
Outlook

• Backscattering effects can be eliminated by implantation in active detectors. Can we also reduce Bremsstrahlung effects?

S.R. Elliot et al., NIMA 273 (1988) 226

M.K. Moe et al., PPNP 32 (1994) 247
Outlook

(AT-TPC, NSCL, W. Mittig et al.)

10X better position resolution in all 3 dimensions.

Test response and track reconstruction with $^{207}$Bi source located inside the TPC.
People and institutions

V. Bader\textsuperscript{1}, D. Bazin\textsuperscript{1}, S. Beceiro-Novo\textsuperscript{1}, M. Bowry\textsuperscript{1}, W. Buhro\textsuperscript{1}, A. Gade\textsuperscript{1}, M. Hughes\textsuperscript{1}, X. Huyan\textsuperscript{1}, S. Liddick\textsuperscript{1}, K. Minamisono\textsuperscript{1}, O. Naviliat-Cuncic\textsuperscript{1}, S. Noji\textsuperscript{1}, S. Paulauskas\textsuperscript{1}, A. Simon\textsuperscript{1}, P. Voytas\textsuperscript{2}, D. Weisshaar\textsuperscript{1}

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