Lecture 10
- Interactions -

Experimental Nuclear Physics PHYS 741

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References and Figures from:
- Basdevant et al., “Fundamentals in Nuclear Physics”
- Henley et al., “Subatomic Physics”
## Lecture Schedule

### Lectures

Note: lectures highlighted in red need to be rescheduled, lectures in blue have been rescheduled.

<table>
<thead>
<tr>
<th>Day</th>
<th>Date</th>
<th>Lecture</th>
<th>Topic</th>
<th>Reading</th>
<th>Homework</th>
<th>Slides</th>
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### Reading Assignment
- chapter 10 in McKeown’s book (on library page)
- handouts
Review - Radiative Decays

Table 4.1. Selection rules for radiative transitions

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<th>type</th>
<th>symbol</th>
<th>angular momentum change</th>
<th>parity change</th>
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<td>E1</td>
<td>1</td>
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</tr>
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<td>E2</td>
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<td>M2</td>
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<td>electric octopole</td>
<td>E3</td>
<td>3</td>
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<td>M3</td>
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<tr>
<td>electric 16-pole</td>
<td>E4</td>
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<tr>
<td>magnetic 16-pole</td>
<td>M4</td>
<td>4</td>
<td>yes</td>
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</table>

![Graph showing radiative decays](image-url)
Review - Internal Conversion

looks like 2-step process classically

-> single quantum process, amplitude can be calculated with perturbation theory

ejection of electron

\[ \frac{7/2^+}{^{137}\text{Cs}} \quad \frac{11/2^-}{^{137}\text{Ba}} \]

\[ \gamma \text{ (90%) internal conversion (10%)} \]

\[ ^{137}\text{Ba internal conversion} \]

\[ ^{137}\text{Cs beta spectrum} \]

\[ \text{electron momentum} \]
Fermi’s Golden Rule

\[ \lambda_{if} = \frac{2\pi}{\hbar} |M_{if}|^2 \rho_f \]
$N \rightarrow N' + e^{-} \quad$ some nuclei emit electrons!

\[ M_{\text{parent}} c^2 \rightarrow E_{\text{daughter}} + E_{\text{electron}} \]

\[ KE_{\text{electron}} = M_{\text{parent}} c^2 - M_{\text{daughter}} c^2 - m_{\text{electron}} c^2 \]

**Fig. 5.** Energy distribution curve of the beta-rays.
Professor Pauli proposed that an undetectable particle shared the energy of beta decay with the emitted electron.
Fermi's Theory of Beta Decay based on Pauli's Letter of Regrets

Experiment: \[ M_n c^2 \neq E_p + E_e \]

Conjecture: \[ M_n c^2 = E_p + E_e + E_\nu \]

Consistency requires that \( E_\nu \) is not observable!

Mr. Fermi's amazingly theory still stands (parity violation added in the 50s).
1949 IN COMO: Pontecorvo, (??), Fermi

Pauli

Pontecorvo

Fermi
<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>1914</td>
<td>Electron Spectrum in $\beta$ decay is continuous</td>
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<tr>
<td>1930</td>
<td>Pauli postulates that a new particle is emitted</td>
</tr>
<tr>
<td>1933</td>
<td>Fermi names the new particle neutrino and introduces four-fermion interaction</td>
</tr>
<tr>
<td>1956</td>
<td>Reines and Cowan discover the neutrino</td>
</tr>
<tr>
<td>1962</td>
<td>At least two neutrinos: $\nu_e \neq \nu_\mu$</td>
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<tr>
<td>1973</td>
<td>Discovery of neutral currents at CERN</td>
</tr>
<tr>
<td>1983</td>
<td>Discovery of the W and Z</td>
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<tr>
<td>1989</td>
<td>Measurement of Z width at CERN $\rightarrow N_\nu=3$</td>
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<tr>
<td>2002</td>
<td>Tau neutrino discovered.</td>
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</table>
Neutron Beta Decay Measurement

\[ n \rightarrow p + e^- + \nu_e \]

- Neutrons
- Polarizing foil
- Scintillators
- B

Scintillator measures electron kinetic energy

Graph showing beta spectrum and background.
Polarized Neutron Decay

\[ n \rightarrow p \, e^- \, \nu_e \]

about 5% more neutrons are emitted in the direction of the neutron spin than opposite the direction

\[ \rightarrow \text{parity is violated} \]

spin is reversed in mirror but direction of electron is not

\[ (\text{mirror} = \text{parity transformation}) \]
Coulomb Correction in Beta Decays

beta-decays of $^{64}$Cu

Momentum spectra from the beta decay of $^{64}$Cu
Fermi’s Theory

\[ N(p) = C p^2 (Q - KE_e)^2 F(Z', p) |M_{fi}|^2 S(p, q) \]

- **Distribution of electron momentum**
- **Statistical factor** derived from the density of final states available to the emitted particles.
- **Matrix element** for allowed transitions gives the strength of the interaction between initial and final states.
- **Shape factor** to correct the matrix element for various types of “forbidden” decay paths.
- **Fermi function** to account for the nuclear coulomb interaction with the emitted particle.

**Graphs:**
- **Electron kinetic energy**
- **Electron momentum**
Selection Rules

radiative decays

weak decays

$\Delta P=0, \Delta J=0$ for Fermi decays

$\Delta P=0, \Delta J=0, +/-1$ for Gamow Teller Decays

(0-> 0 forbidden)
Beta-Decay in Nuclei

\[ ^{13}\text{N} \ 1/2^+ \quad \rightarrow \quad ^{13}\text{C} \ 1/2^+ \]

decay without spin-flip shown, decay with and without spin-flip possible

\[ ^{14}\text{O} \ 0^+ \quad \rightarrow \quad ^{14}\text{N} \ 0^+ \quad \rightarrow \quad ^{14}\text{N} \ 1^+ \]

predominantly to first excited state, followed by radiative decay
Beta-Decays

$^{14}\text{O} \rightarrow ^{14}\text{N}$ decay

$0^+ \rightarrow 0^+$ decay

purely Fermi decay
$\beta^{+/-}$ Decay of $^{40}\text{K}$
Beta Decay Transition Rates of Superallowed Decays

phase space integral

\[ Q_{\beta}^5 \]

reduced rate due to Coulomb corrections

Cabibbo suppression
Electron Capture

(a) 

\( (A,Z) \) 

\( k, l, m \) 

(b) 

\( (A,Z-1) \) 

\( 1, m \) 

(c) 

\( (A,Z-1) \) 

\( \gamma \) 

Auger electron
Auger Electrons

- proton
- K-shell electron
- L-shell electron
- M- or outer-shell electron

2.5MeV protons

"Auger electron"
$\nu_e \ ^{71}\text{Ga} \rightarrow e^- \ ^{71}\text{Ge}$

**Diagram Description:**
- **Add 1 mg of carrier**
- **Expose 3 - 4 weeks**
- **Fill a counter**
- **Extract**
- **6 months counting**

**Experimental Setup:**
- GaCl$_3$ + HCl
- (54 m$^3$, 110 l)
- $N_2$ + GeCl$_4$
- $H_2O$ + GeCl$_4$
Auger Electrons from EC on $^{71}\text{Ge}$

$^{71}\text{Ge}$ decays by K (87.7%), L (10.3%), and M (2.0%) electron capture.

Energy deposition from Auger electrons and X-rays emitted in the decay results in an energy spectrum with two peaks: an L peak at 1.2 keV and a K peak at 10.4 keV.
atom \sim 10^{-8} \text{ cm}

nucleus \sim 10^{-12} \text{ cm}

proton (neutron) \sim 10^{-13} \text{ cm}

electron < 10^{-16} \text{ cm}

quark < 10^{-16} \text{ cm}