Literature

- Judith und Lothar Oberauer: Neutrinophysik
- Giulia Ricciardi: Introduction to Neutrino and Particle Physics (2024!)
- Grimus: Neutrino Physics - Theory
- Akhmedov: Neutrino Physics

Why important?

Lecture 2: Neutrinos in the SM

- Massless in SM → Probe physics beyond SM
- Astrophysics and cosmology: understanding stellar evolution, SN, nuclear fusion processes, DM candidate, messengers for extragalactic sources

→ Lecture 13

Possible applications:

- Reactor monitoring
- Geological surveys
- Communication

Even if no direct benefit, still interesting for understanding of our Universe

Neutrino Physics: Theory and experiment

Neutrino sources

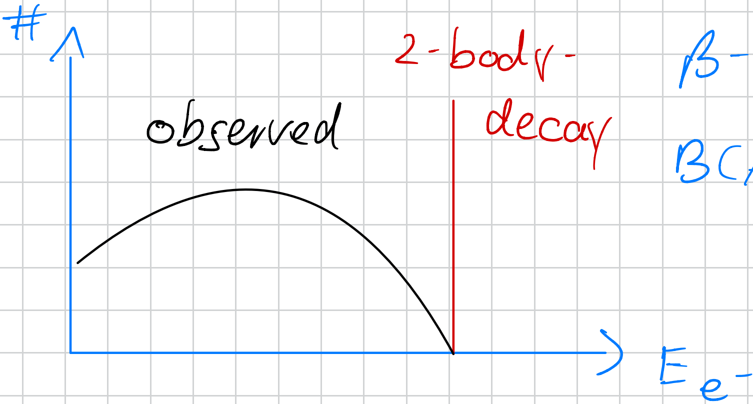
- natural
  - Earth
  - Sun
  - Atmosphere
  - Supernovae
- artificial
  - nuclear reactors
  - accelerator

Lecture 3

Neutrino detectors

- scintillators
- Cerenkov
- radiochemical
- semiconductor
- cryogenic / liquid noble gases

1930 Wolfgang Pauli: letter



β-decay:

$$B(A,Z) \to C(A,Z+1) + e^- \ (+\bar{\nu}_e)$$

$$E = m_B - m_C$$

Problem 1: Energy conservation
Problem 2: Angular momentum conserv.
False spin statistics!
A even ⇒ integer spin
A uneven ⇒ half numbered spin
β-decay: Spin of parent and daughter the same, but e^- is Spin $1/2$!

Predicted neutrino properties:
- electrically neutral (charge conserv.)
- small mass (endpoint of spectrum)
- Spin $1/2$
- weakly interacting

Pauli called new particle „neutron"

1932: Chadwick: discovery of neutron
1933/34 Fermi: Theory of β-decay
Assumed neutrino chargeless and massless
Fermi's Golden Rule: $\frac{1}{\tau} = \frac{2\pi}{\hbar} |M_{if}|^2 \rho_f$

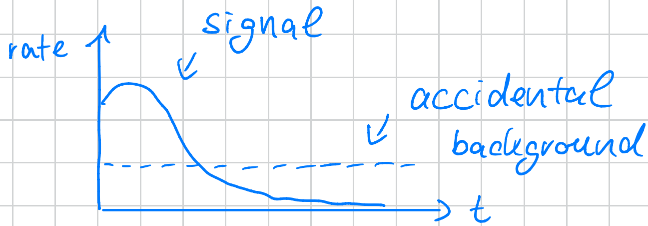
$\frac{1}{\tau}$ → life-time; M_{if} → interaction strength; ρ_f → density final states

1956 Reines / Cowan: First detection

New sources: Fission bombs and reactors (NP95)

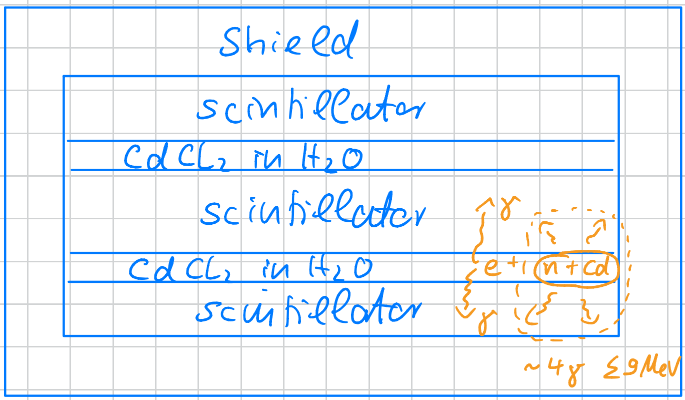
IBD: $\bar{\nu}_e + H^+ \longrightarrow n + e^+$ (predicted by Fermi)

Coincidence signal



Pioneering technology — Lecture 6: reactor $\bar{\nu}_e$

Underground (12 m w.e. overburden)



Target mass ~ 400 l

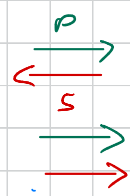
1957 Wu: parity non-conservation

Max. violated!

Weak boson coupling:

particles → left handed (h = −1)

antiparticles → right handed (h = +1)



1962 Discovery of muon neutrino NP 88

Pion-decay: $\pi^- \rightarrow \mu^- + \bar{\nu}$ — Lepton number conserv.

Detection: $\bar{\nu} + p \rightarrow n + e^+$ (1)

$\bar{\nu} + p \rightarrow n + \mu^+$ (2)

$\nu_e = \nu_\mu$: (1) and (2); $\nu_e \neq \nu_\mu$: only (2)

1968 Homestake solar neutrino experiment NP 2002

Fusion reaction: $4p + 2e^- \rightarrow {}^4He^{++} + \underline{2\nu_e}$

615 t perchlorethylene (C_2Cl_4) Lecture 5

$^{37}Cl + \nu \longrightarrow {}^{37}Ar + e^-$ few atom counting

($^{37}Ar \rightarrow {}^{37}Cl$: e^--capture (35 d))

Solar neutrino problem: less ν than expected...

- Solar model wrong?
- Measurement wrong?
- Neutrino properties?

astroparticle physics: interplay between particle and astrophys.

1987 Kamiokande: Supernova neutrinos

Massive star: $e^- + p \longrightarrow n + \nu$

Core collapse: production high E gammas and lepton pairs

main process for ν production

$e^+ + e^- \longrightarrow \nu_\alpha + \bar{\nu}_\alpha$

99 % of energy released by neutrinos!

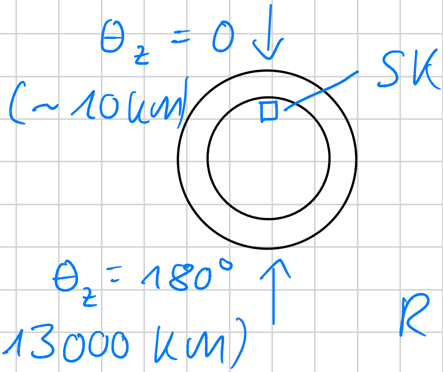
Detection in H_2O Cerenkov detector → Lecture 4

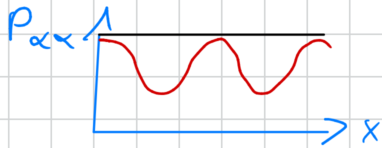
1998 / 2001 Neutrino oscillations NP2015

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavor eigenstates linear combination of mass eigenstates

Superkamiokande





(50000 t!
>10000 PMTs)

$$R = (\mu/e)_{data} / (\mu/e)_{model}$$

SNO Lecture 5

$$\phi^{data}_{CC} / \phi^{model}_{NC} \sim 1/3 \quad (\nu_e) \qquad \phi^{data}_{NC} / \phi^{model}_{NC} \sim 1 \quad (\nu_x)$$

Transition probability: $P_{\alpha\beta}(l) \propto \sin^2\left(\frac{c \Delta m\, l}{E}\right)$

Lecture 7 – 9 (2 th. + 1 exp.)

=> neutrinos have mass! (BSM)

2000 Observation of τ neutrino

- Produce ν_τ beam : $D_s(c\bar{s}) \to \tau + \nu_\tau$
- Create τ lepton in target medium
- Detect τ-decay (e.g. $\tau \to e + \nu_\tau + \nu_e$)

2017 Coherent elastic ν - nucleus scattering

High cross-section ! Lecture 14

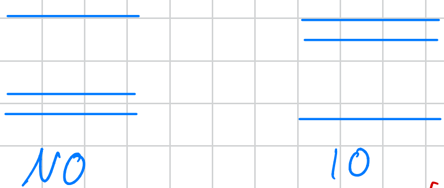
Open questions:

- Absolute neutrino mass ?

  KATRIN : endpoint of tritium decay spectrum

  Holmium: Loredana Gastaldo (MPIK!)

  e^- - capture
- Mass hierarchy : ordering of mass eigenstates



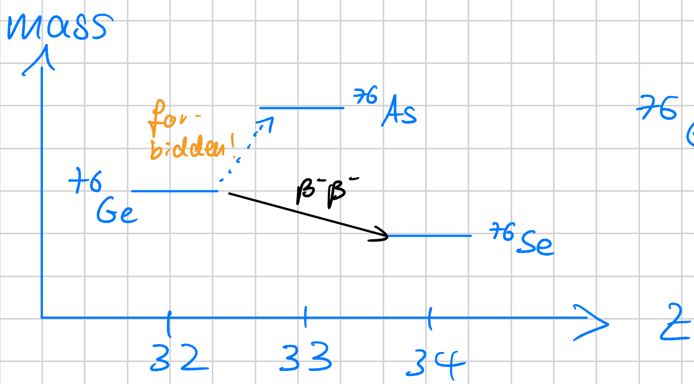
JUNO

→ Lecture 11 + 12

- Are there sterile neutrinos ?
- CP violation in leptonic sector ?
- Majorana vs Dirac : Is neutrino its own antiparticle ?

only possible for ν ! No mass via SM Higgs mech. ← ("

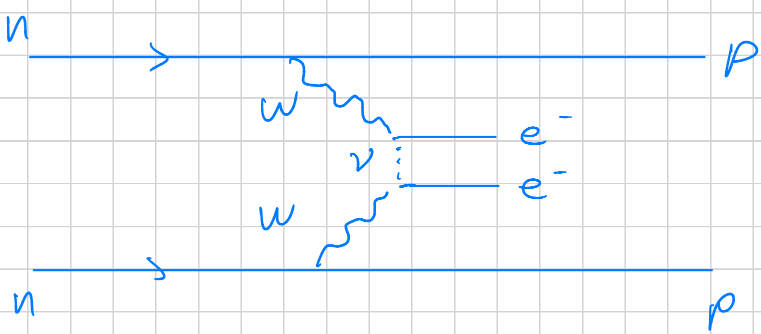
Neutrinoless ββ-decay — Lecture 10



$$^{76}Ge \rightarrow {}^{76}Se + 2e^- + 2\bar{\nu}_e$$

$$T_{1/2} = 2 \cdot 10^{21}\, y$$

Neutrinoless ββ-decay? Lepton number violat!



only if ν Majorana!

Extract information on
- particle type
- neutrino mass
- mass hierarchy