Introduction to Nuclear and Particle Physics

Lesson 13

p-parity and c-parity

nuclear power

Warm-up question 1

Which statements about parity and C parity are correct?

A) The combined P-parity of a fermion-anti-fermion pair is always 1

B) All fully neutral particles transform under charge parity operation as $\mathbf{C}\left|\psi_{\mathbf{0}}\right\rangle = +\left|\psi_{\mathbf{0}}\right\rangle$

C) The π_0 decay into three photons is not allowed since it does not conserve charge parity.

D) The C-parity of ortho-positronium (S=1) is similar to its P-parity

Warm-up question 2

Which statements about nuclear pressure-water reactors are correct?

A) The reactor should not be operated in chain reaction because it is not controllable in this state.

B) The water is kept under pressure in order to avoid it from boiling away.

C) Usually the fast neutrons from nuclear fission are directly absorbed again by the next nucleus.

D) The only purpose of the water is to cool the core.

What do we do today?

Parity

General rules

MC questions

C parity

Selection rules

Examples

Nuclear reactors

Neutrons, fissions, moderators

Parity & Co - examples and hints

Some parities and spins

	Spin	Parity
e^-	1/2	
e^+	1/2	–
p^+	1/2	+
n	1/2	
π^+		–
π^-		
γ	1	
${}^{16}_{8}O_8$		
${}^{15}_{8}O_7$		–

General rules to remember:

Rules for nuclei:

Some parities and spins

	Spin	Parity
e^-	1/2	+
e^+	1/2	−
p^+	1/2	+
n	1/2	+
π^+	0	−
π^-	0	−
γ	1	−
${}^{16}_{8}O_8$	0	+
${}^{15}_{8}O_7$	1/2	−

General rules to remember:

Fermions have parity +1

Anti-Fermions have parity -1

Bosons have same parity as their anti-partners

example: $P\left(\left|K^+K^-\right\rangle\right) = 1$

Rules for nuclei:

- Full shells have 0^+
- One-nucleon states or holes define spin and parity of whole nucleus

Question 10 (*2 Points*) Consider the hypothetical decay

$$\mathrm{n} \rightarrow \mathrm{p} + \gamma.$$

Which conservation law(s) is(are) violated in this process?

A) Charge.
B) Energy.
C) Angular momentum.
D) Lepton number.
E) Baryon number.
F) None of the other answer options is correct.

Question 10 (*2 Points*) Consider the hypothetical decay

$$\mathrm{n} \rightarrow \mathrm{p} + \gamma.$$

Which conservation law(s) is(are) violated in this process?

- ■ Charge.
- ☐ Energy.
- ☐ Angular momentum.
- ☐ Lepton number.
- ☐ Baryon number.
- ☐ None of the other answer options is correct.

Question 9 (*2 Points*) Consider the hypothetical decay

$$n \rightarrow p + \pi^{+}.$$

Which conservation law(s) is(are) violated in this process?

A) Isospin (strong Isospin).
B) Charge.
C) Energy.
D) Parity.
E) Lepton number.
F) Baryon number.

Question 9 (*2 Points*) Consider the hypothetical decay

$$\mathrm{n} \rightarrow \mathrm{p} + \pi^+ .$$

Which conservation law(s) is(are) violated in this process?

- [x] Isospin (strong Isospin).
- [x] Charge.
- [x] Energy.
- [x] Parity.
- [ ] Lepton number.
- [ ] Baryon number.

Question 7 (*2 Points*) Consider the hypothetical decay

$$n \rightarrow p + e^- .$$

Which conservation law(s) is(are) violated in this process?

A) Isospin (strong isospin).

B) Charge.

C) Energy.

D) Angular momentum.

E) Lepton number.

F) Baryon number.

Question 7 (*2 Points*) Consider the hypothetical decay

$$n \to p + e^- .$$

Which conservation law(s) is(are) violated in this process?

- ■ Isospin (strong isospin).
- □ Charge.
- □ Energy.
- ■ Angular momentum.
- ■ Lepton number.
- □ Baryon number.

Gamma decays / electromagnetic transitions

Life times of γ decays are comparably long

- *em force much weaker than strong force*
- *wave length of photon much longer than nuclear size*
- *Photon spin requires angular momentum transition*

typically $\tau \sim 10^{-12}\ s$

- fastest: $10^{-19}\ s$

Selection rules

gamma(s) carry away at least $\Delta j = 1$

In general: $\left|J_i - J_f\right| \leq \Delta j \leq J_i + J_f$

J = total spin of nucleus (initial/final)

Multipole expansion and parity change

Electric multipole transitions

$E_1, E_2, \ldots\ E_{\Delta j}$ $\qquad$ $\mathrm{P}\left|f\right\rangle = (-1)^{\Delta j}\ \mathrm{P}\left|i\right\rangle$

Magnetic multipole transitions

$M_1, M_2, \ldots\ M_{\Delta j}$ $\qquad$ $\mathrm{P}\left|f\right\rangle = (-1)^{\Delta j+1}\ \mathrm{P}\left|i\right\rangle$

Gamma decays / electromagnetic transitions

Electric

$$P\left|f\right\rangle = (-1)^{\Delta j}\; P\left|i\right\rangle$$

Magnetic

$$P\left|f\right\rangle = (-1)^{\Delta j+1}\; P\left|i\right\rangle$$

Which type of γ decay can cause the nuclear transition $\frac{5}{2}^{+} \longrightarrow \frac{3}{2}^{-}$ **?**

Workflow:

A) Determine possible Δj $\quad \Delta j = 1\ldots4$

B) check parity $\quad E_1, M_2, E_3, M_4$

Question 9 *(2 Points)*

A nuclear excited state decays by an $E2$ transition into a state with parity and spin of $\frac{3}{2}^{+}$. Which of the following spin and parity assignments could represent the excited state?

A) $\frac{5}{2}^{+}$

B) $\frac{5}{2}^{-}$

C) $\frac{7}{2}^{+}$

D) $\frac{7}{2}^{-}$

E) $\frac{9}{2}^{-}$

F) $\frac{1}{2}^{-}$

Electric

$$P\,|f\rangle = (-1)^{\Delta j}\; P\,|i\rangle$$

Magnetic

$$P\,|f\rangle = (-1)^{\Delta j+1}\; P\,|i\rangle$$

Question 9 *(2 Points)*

A nuclear excited state decays by an $E2$ transition into a state with parity and spin of $\frac{3}{2}^+$. Which of the following spin and parity assignments could represent the excited state?

- [x] $\frac{5}{2}^+$
- [ ] $\frac{5}{2}^-$
- [x] $\frac{7}{2}^+$
- [ ] $\frac{7}{2}^-$
- [ ] $\frac{9}{2}^-$
- [ ] $\frac{1}{2}^-$

Electric

$$P\left|f\right\rangle = (-1)^{\Delta j}\ P\left|i\right\rangle$$

Magnetic

$$P\left|f\right\rangle = (-1)^{\Delta j+1}\ P\left|i\right\rangle$$

Charge conjugation and c-parity

The charge conjugation operation transforms charged particles into their anti-particles.

$$\mathbf{C}\left|\psi\right\rangle = \left|\bar{\psi}\right\rangle$$

C reverses all internal quantum numbers
(charge, baryon/lepton number, strangeness,…)

Only few, neutral particles are eigenstates of C (anti-particles of themselves)

$$\mathbf{C}\left|\psi\right\rangle = \mathbf{n_C}\left|\psi\right\rangle \qquad n_C = \pm 1$$

Examples:

Photon $\mathrm{C}\left|\gamma\right\rangle = -\left|\gamma\right\rangle$

$\mathrm{C}\left|\mathrm{n}\gamma\right\rangle = (-1)^{\mathrm{n}}\left|\mathrm{n}\gamma\right\rangle$

π_0 $\mathrm{C}\left|\pi_0\right\rangle = +\left|\pi_0\right\rangle$

Fermion-anti-fermion $\mathrm{C}\left|\mathrm{f}\bar{\mathrm{f}}\right\rangle = (-1)^{\mathrm{L+S}}\left|\mathrm{f}\bar{\mathrm{f}}\right\rangle$

Spin-zero pair $\mathrm{C}\left|\pi^+\pi^-\right\rangle = (-1)^{\mathrm{L}}\left|\pi^+\pi^-\right\rangle$

Charge conjugation and c-parity

$$C\left|\gamma\right\rangle = -\left|\gamma\right\rangle \qquad C\left|f\bar{f}\right\rangle = (-1)^{L+S}\left|f\bar{f}\right\rangle$$

$$C\left|n\gamma\right\rangle = (-1)^{n}\left|n\gamma\right\rangle$$

$$C\left|\pi_0\right\rangle = +\left|\pi_0\right\rangle \qquad C\left|\pi^+\pi^-\right\rangle = (-1)^{L}\left|\pi^+\pi^-\right\rangle$$

The neutral pion decays into two photons, $\pi^0 \to \gamma + \gamma$. What is the C−parity of π^0?

$$\pi^0 \to \gamma + \gamma$$
$$C_\pi = C(2\gamma) = (-1)^2 = 1\ .$$

Charge conjugation and c-parity

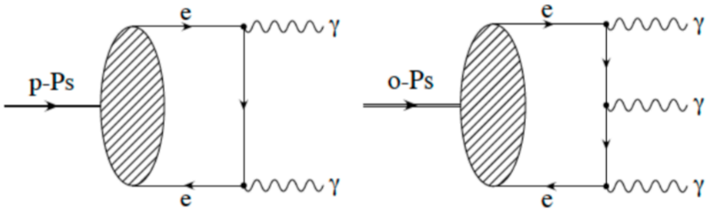
$$C\left|\gamma\right\rangle = -\left|\gamma\right\rangle \qquad C\left|f\bar{f}\right\rangle = (-1)^{L+S}\left|f\bar{f}\right\rangle$$

$$C\left|n\gamma\right\rangle = (-1)^{n}\left|n\gamma\right\rangle$$

$$C\left|\pi_0\right\rangle = +\left|\pi_0\right\rangle \qquad C\left|\pi^+\pi^-\right\rangle = (-1)^{L}\left|\pi^+\pi^-\right\rangle$$

Positronium Ps is an atom made of an electron and positron. It is a short lived system and decays electromagnetically into photons. Positronium has two ground states: Para-positronium ($L = 0$ and $S = 0$) and ortho-positronium ($L = 0$ and $S = 1$).

Into how many photons do the two states decay?



Charge conjugation and c-parity

$C\,|\gamma\rangle = -\,|\gamma\rangle$

$C\,|f\bar{f}\rangle = (-1)^{L+S}\,|f\bar{f}\rangle$

$C\,|n\gamma\rangle = (-1)^{n}\,|n\gamma\rangle$

$C\,|\pi_0\rangle = +\,|\pi_0\rangle$

$C\,|\pi^+\pi^-\rangle = (-1)^{L}\,|\pi^+\pi^-\rangle$

Let's have a look at Positronium in the 2^3S_1 atomic state (notation $n^{2S+1}L_J$).

What are the P-parity and the C-parity of this atom?

$$2^3S_1$$

C-parity $\quad (-1)^{L+S} = (-1)^{0+1} = -1$

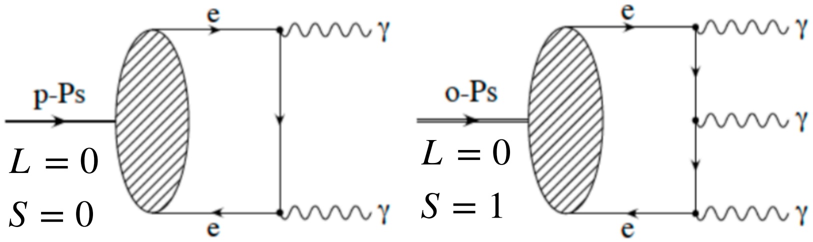
P-parity $\quad (-1)^{L}(-1)(+1) = -1$

Now consider an electromagnetic transition into state 2^3P_1. Which components do we need to include for the parities of the final state?

$$\text{Parity}_{final} = \text{Parity}\,(Ps) \cdot \text{Parity}\,(\gamma) \cdot \text{Parity}\,(l_\gamma)$$

$(-1)^n \qquad (-1)^{l_\gamma}$

C-Parity and P-Parity



$C\,|n\gamma\rangle = (-1)^n\,|n\gamma\rangle$ $\quad$ $C\,|f\bar{f}\rangle = (-1)^{L+S}\,|f\bar{f}\rangle$

contradiction?

No, because γs can have $l_\gamma \neq 0$ here.

$P\,|n\gamma\rangle = \underline{(-1)^{l_\gamma}}(-1)^n\,|n\gamma\rangle$ $\quad$ $P\,|f\bar{f}\rangle = (-1)^L\cdot(1)\cdot(-1)\,|f\bar{f}\rangle$

Photons from bound system can have $l_\gamma \neq 0$:

"The photon emitted by e.g., a nucleus can carry orbital angular momentum as it can be emitted not exactly from the center of the nucleus. Hence in this case the photon total angular momentum is not simply given by its spin."

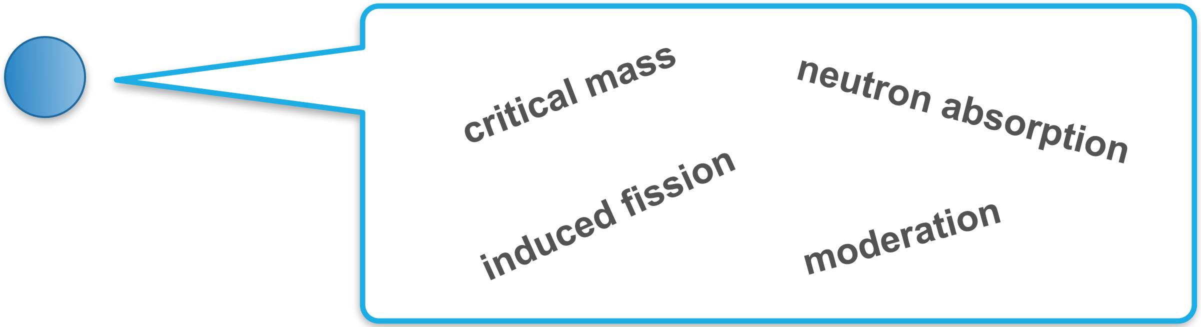
Group activity

The path of the neutron in a fission reactor

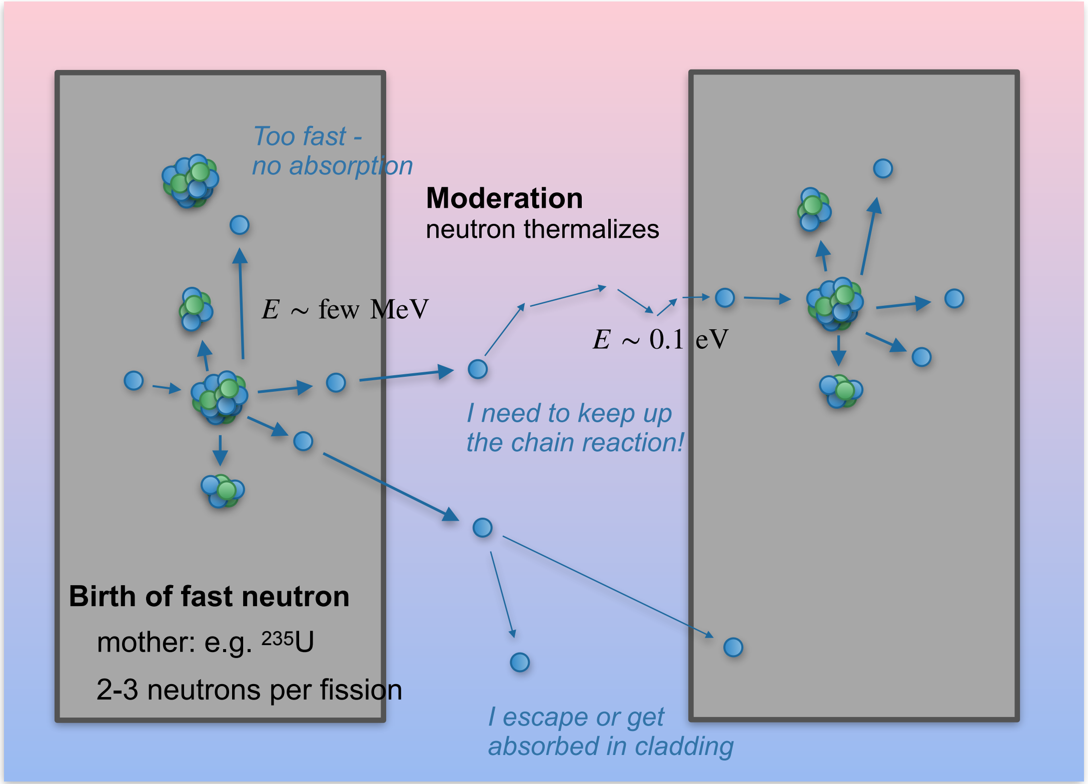
Group activity: How does the life of a neutron in the core of a fission reactor look like?

In groups, please prepare the biography of a neutron in the reactor (can be a small cartoon, story, scheme,…).

The following words might help you:



The path of the neutron in a fission reactor



Chain reaction:

Amount of neutrons produced
by fissions larger than neutron loss

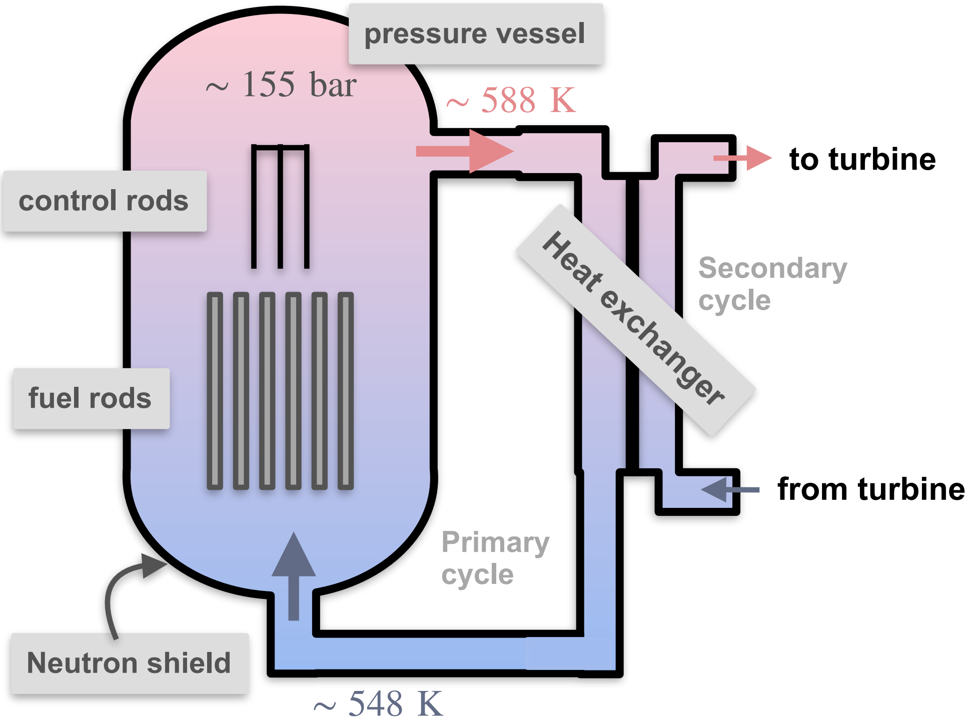
$\Rightarrow$ **Subsequent fissions do not stop**

Critical mass:

Amount of radioactive material
needed to sustain chain reaction

depends on geometry!

Scheme of a pressure water reactor



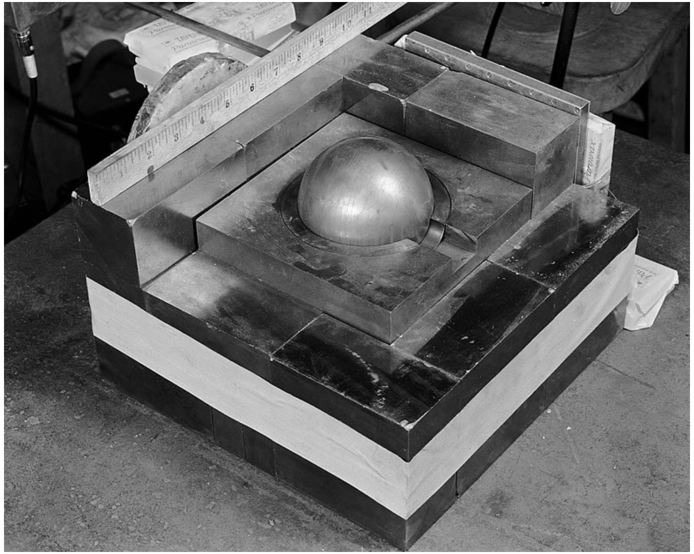
Geometry of core optimized for homogeneous criticality

Role of water:

- Coolant to extract thermal energy
- Moderator for neutrons
- Safety feedback:

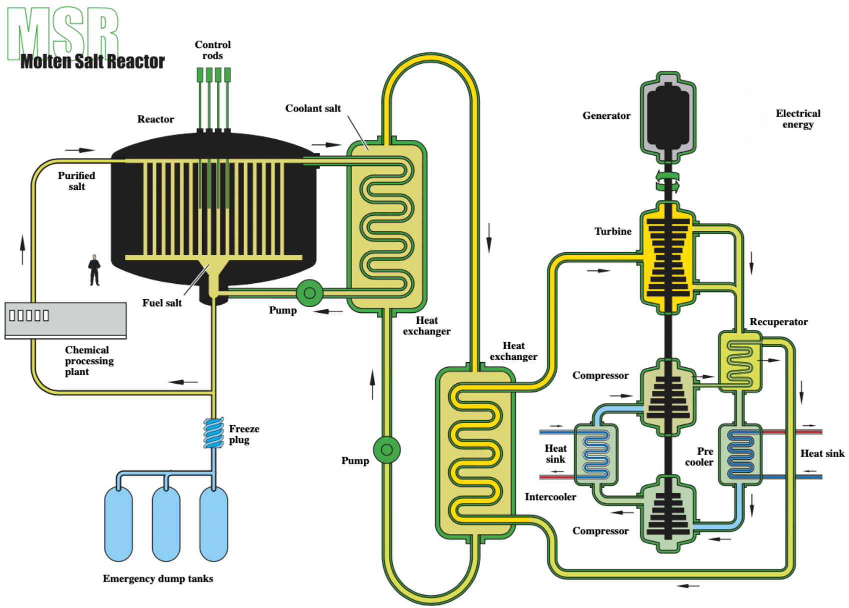
$$T \uparrow \longrightarrow \rho \downarrow \Longrightarrow \text{less moderation}$$

The "demon core" and critical mass



Two deadly incidents in Los Alamos when scientists played with neutron reflectors

Example for generation IV: Molten salt reactor



https://www.youtube.com/watch?v=aqPLU8ge-0w

Warm-up question 1

Which statements about parity and C parity are correct?

A) The combined P-parity of a fermion-anti-fermion pair is always 1

B) All fully neutral particles transform under charge parity operation as $\mathbf{C}\left|\psi_{\mathbf{0}}\right\rangle = +\left|\psi_{\mathbf{0}}\right\rangle$

C) The π_0 decay into three photons is not allowed since it does not conserve charge parity.

D) The C-parity of ortho-positronium (S=1) is similar to its P-parity

Warm-up question 1

Which statements about parity and C parity are correct?

is $(-1) \cdot (-1)^L$

A) The combined P-parity of a fermion-anti-fermion pair is always 1

eigenvalue an also be -1,
example: photon has c-parity -1

B) All fully neutral particles transform under charge parity operation as $\mathbf{C}\left|\psi_0\right\rangle = +\left|\psi_0\right\rangle$

✓ The π_0 decay into three photons is not allowed since it does not conserve charge parity.

✓ The C-parity of ortho-positronium (S=1) is similar to its P-parity

C-parity: $(-1)^{L+S}$
P-parity: $(-1)^L \cdot (-1)$

Warm-up question 2

Which statements about nuclear pressure-water reactors are correct?

A) The reactor should not be operated in chain reaction because it is not controllable in this state.

B) The water is kept under pressure in order to avoid it from boiling away.

C) Usually the fast neutrons from nuclear fission are directly absorbed again by the next nucleus.

D) The only purpose of the water is to cool the core.

Warm-up question 2

Which statements about nuclear pressure-water reactors are correct?

A) The reactor should not be operated in chain reaction because it is not controllable in this state.

The water is kept under pressure in order to avoid it from boiling away.

C) Usually the fast neutrons from nuclear fission are directly absorbed again by the next nucleus.

D) The only purpose of the water is to cool the core.