Decays and Conservation Laws

Recall that in a particle decay we have

$$\text{Particle}_1 \Rightarrow \text{Particle}_2 + X$$

All our usual conservation laws apply

- → Conservation of Energy
- → Conservation of Momentum
- → Conservation of Angular Momentum
- → Conservation of charge

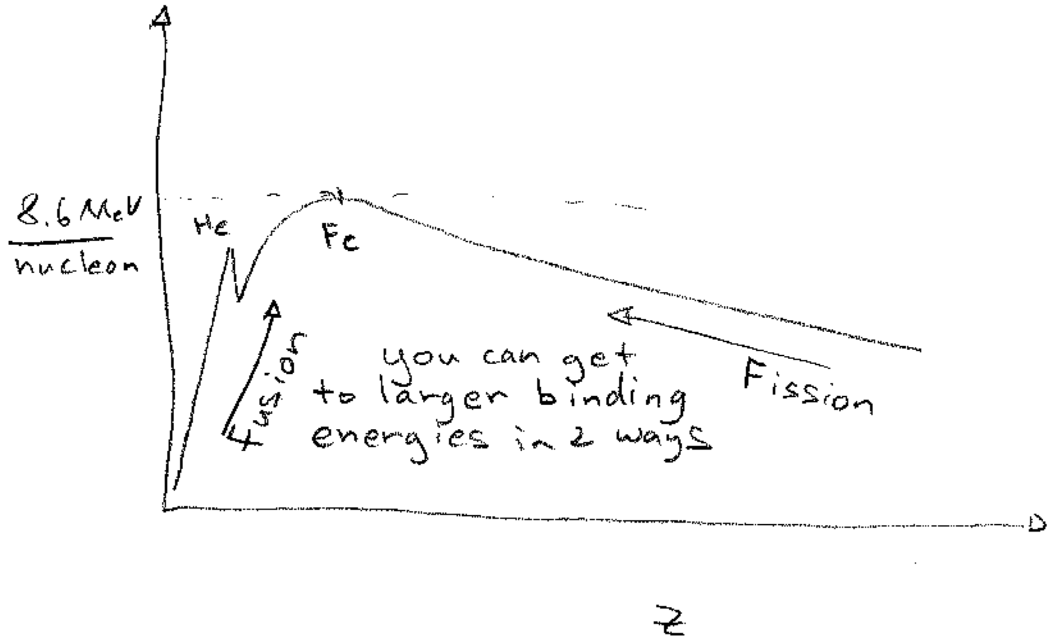
If $Q = M_1c^2 - M_2c^2 - M_xc^2 > 0$, the products of the decay will acquire some kinetic energy. Indeed, you must have $Q > 0$ for a decay to occur in the 1st place.

Sometimes you lose some of this energy to particles you can't see. In β decay, one of the products is a neutrino. This particle interacts with matter very rarely.

How rarely? As a rule of thumb, you might expect one neutrino from the sun to interact in your body once in your lifetime.

So how does the sun make neutrinos?

If you recall our binding energy plot it looked like



In fission, a heavy nucleus fragments into several smaller ones. Typically, we get about $\frac{1\,\text{MeV}}{\text{nucleon}}$ for the released energy. (Don't get to use all of the energy though)

Reminder:

It is ok to write out the energy given up as on the view graph since in Beta decay

$$ {}^{A}_{Z}X \rightarrow \underbrace{{}^{A}_{Z+1}X + e^{-}}_{\substack{\text{can lump electron} \\ \text{in since } Z+1 \text{ needs} \\ \text{one more and the} \\ \text{diffence is slight}}} + \bar{\nu} $$

Take a minute to talk about angular momentum conservation.

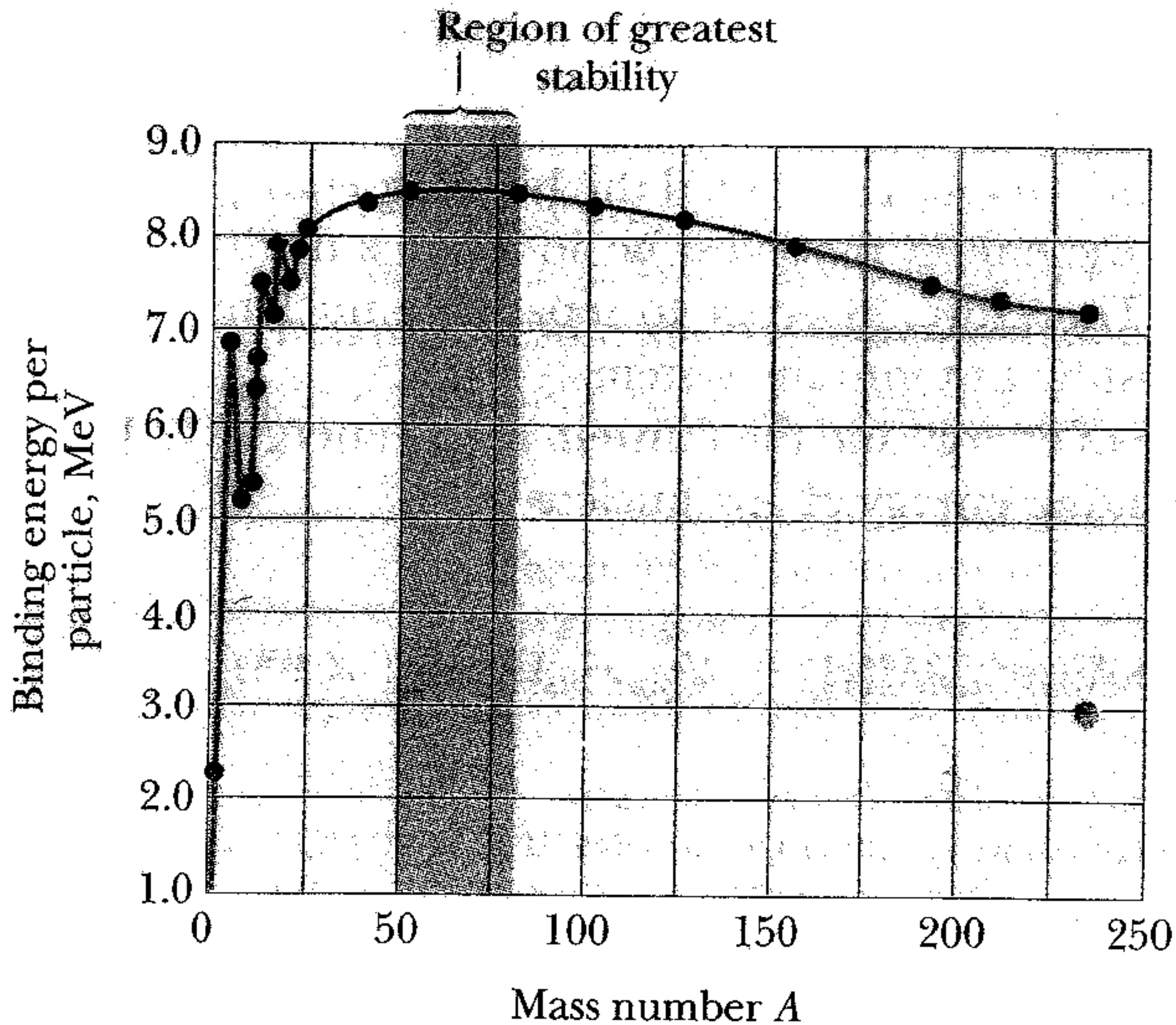
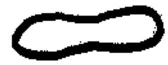


Figure 30.9 A plot of binding energy per nucleon versus mass number for the stable nuclei in Figure 30.3.

One Fission Reaction

$${}^{1}_{0}n + {}^{235}_{92}U \Rightarrow {}^{236}U^{*}$$



$${}^{236}_{92}U^{*} \Rightarrow {}^{144}Ba + {}^{89}Kr + 3\,{}^{1}_{0}n$$

can be reused

$${}^{144}Ba \Rightarrow {}^{144}La + \beta^{-} + \bar{\nu}_e$$
$$\hookrightarrow {}^{144}Cs + \beta^{-} + \bar{\nu}_e$$
$$\hookrightarrow {}^{144}Pr + \beta^{-} + \bar{\nu}_e$$
$$\hookrightarrow {}^{144}Nd + \beta^{-} + \bar{\nu}_e$$

$${}^{89}Kr \Rightarrow {}^{89}Rb + \beta^{-} + \bar{\nu}_e$$
$$\hookrightarrow {}^{89}Sr + \beta^{-} + \bar{\nu}_e$$
$$\hookrightarrow {}^{89}Y + \beta^{-} + \bar{\nu}_e$$

Net effect

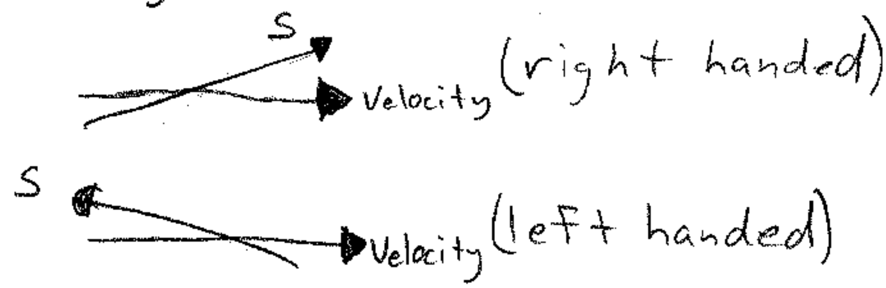
$${}^{235}U \Rightarrow {}^{89}Y + {}^{144}Nd + 2\,{}^{1}_{0}n$$

and the "Q" value for this reaction is

$$Q = (235.044057 - 88.905847 - 143.910082)c^2$$
$$-2(1.008665)c^2 = 0.211uc^2 \cdot 931.5\,\frac{MeV}{uc^2}$$
$$= 196.36\ MeV$$

or about 1 MeV for each nucleon in the process

I typically have a hard time remembering when to use $\bar{\nu}_e$ or ν_e, but I seem to be able to remember that a neutrino is a left handed particle. What does this mean? Well, for a given direction, a particle can have it's spin either along the direction of travel or not



It turns out electrons & positrons can be either left or right handed, but neutrinos are always left handed. There was a famous experiment performed in the 1950's to determine that this funkiness happened.

It turns out $^{60}Co \rightarrow {}^{60}Ni + e^- + \bar{\nu}_e$

but ^{60}Co is in a $J=5$ state
and ^{60}Ni is in a $J=4$ state

You can align the ^{60}Co spins using a very strong magnetic field. Since angular momentum is conserved in this decay, we expect the electron and the anti-neutrino to be ejected from the nucleus with their spins alighed.

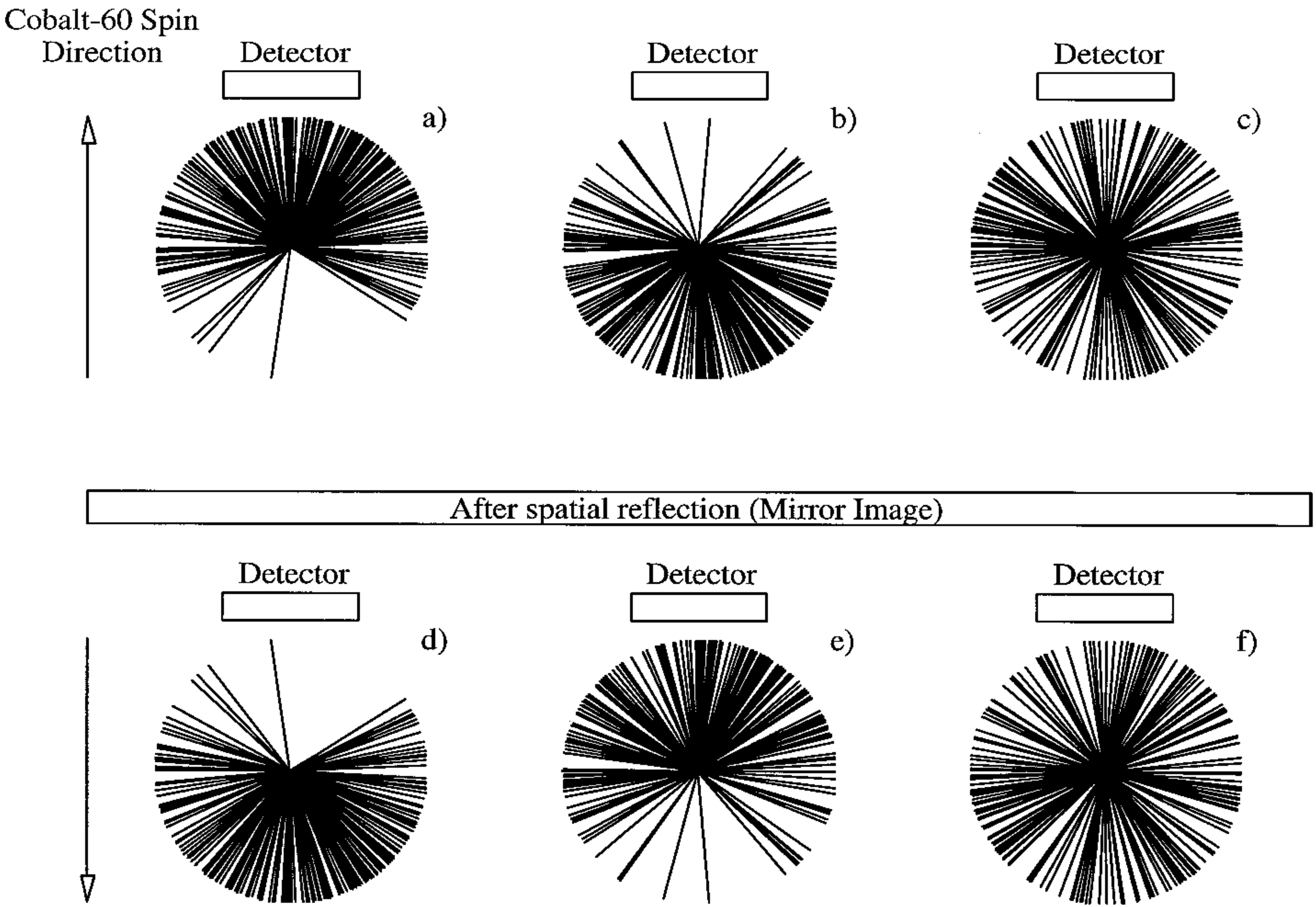
$$\uparrow {}^{60}Co \Rightarrow \uparrow {}^{60}Ni + \uparrow e^- + \uparrow \bar{\nu}_e$$

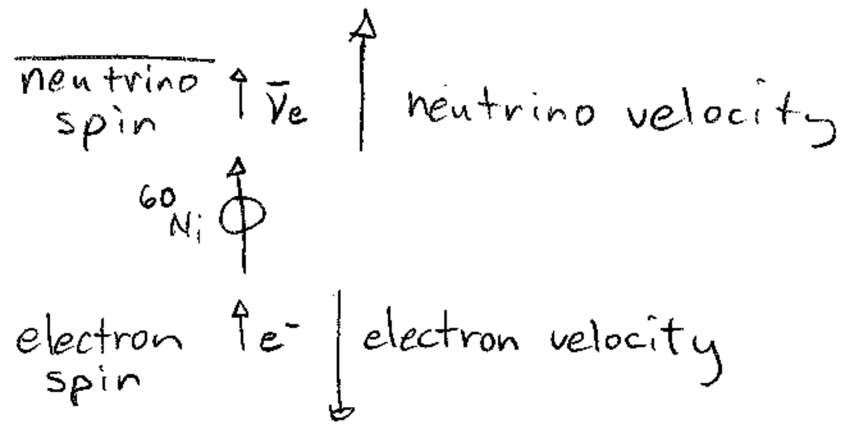
So, here's the trick. You count the number of decays with a detector placed where the spins of the ^{60}Co atoms point to. Then you repeat the experiment, but you switch the direction of the magnetic field you are using. When they performed the experiment, 3 possibilities were expected (see view graph)

They always saw that the electrons prefered to be ejected opposite to the direction of the ^{60}Co spin (or the magnetic field).

- Since the electron can have it's spin any direction
- The $\overline{\text{neutrino}}$ must be prefering a direction to place it's spin

$\Rightarrow$ Parity violation - experiment does not behave the same way upon reflection.


Cobalt-60 Spin Direction
Detector
a)
Detector
b)
Detector
c)
After spatial reflection (Mirror Image)
Detector
d)
Detector
e)
Detector
f)

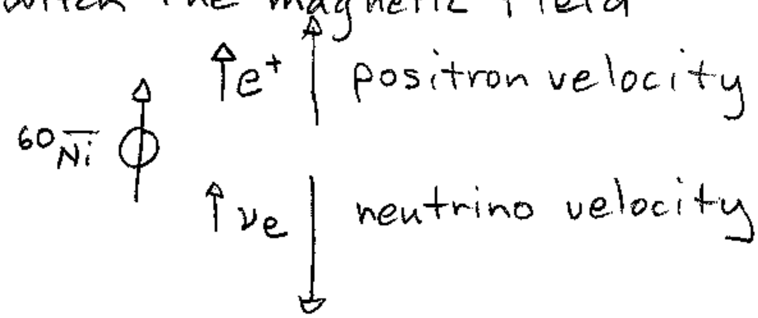


anti-neutrino's are right handed
neutrino's are left handed

Interestingly, if you replace everything by it's antiparticle (called a "C" or charge transformation)

$$^{60}\overline{Co} \downarrow \;\Rightarrow\; \downarrow {}^{60}\overline{Ni} + b e^+ + b \nu_e$$

& switch the magnetic field



your detector would read the same

so these type of decays do not violate CP in this description.

(They do in others!)

Neutrinos were first discovered by looking at the copious number that come out of a nuclear reactor (you can shut it off and on). There was a pretty convincing case already.

Enrico Fermi was able to show in the 30's that the rate of decay of a neutron-proton looks like

$$(\text{a constant})\left(\begin{matrix}\text{difference between}\\ \text{initial \& final states}\end{matrix}\right)\left(\begin{matrix}\text{density of}\\ \text{states}\end{matrix}\right)$$

if we had one particle decaying into 2, the energies would be well defined.

For one particle decaying into 3, we can leave the heavy proton at rest and consider the density of states for the electron and the neutrino $p_{\bar{\nu}_e}^2 d\bar{\nu}_e \, p_{e^-}^2 dp_{e^-}$

(collapses the integral)

we know that $E_{\bar{\nu}} \sim p_{\bar{\nu}}$ & $\overline{E_{\bar{\nu}} + E_{e^-} \approx \text{constant}} = E_{max}$

$$(\#\text{ decays with } p_e) \quad \propto \left(E_{max} - E_{e^-}\right)^2 p_e^2 \, dp_e$$

$$\left(\frac{\#\text{ of decays with } p_e}{dp_e}\right) \propto \left(E_{max} - E_{e^-}\right)^2 p_e^2$$

Which is where the plot in your book comes from