▶ Q1

There can be multiple violations in each example, so watch out.

(a) Clearly a violation of lepton flavor. Also, wouldn't an on-shell photon have no energy to contributre to the electron and antimuon mass?

(b) The on-shell W^+ boson has less mass than a top quark, so this cannot occur. I think weak interactions don't care about quark flavor conservation

(c) Charge and lepton flavor violation.

(d) Acceptable. Quark flavor is fine due to weak force. 173.1 > 80.39 + 4.18 energy is conserved. Now we know the next four are false.

(e) Lepton flavor violation. Would be fine if antineutrino, I think that one is on the PDG.

(f) Energy violation again with an "on-shell" photon? To be precise, since E=pc for a photon (m=0) and there is zero momentum on-shell, this cannot exist due to energy & momentum conservation.

(g) quark flavor violation, no weak forces seen here. Also lepton number/flavor.

(h) energy violation, Z is much heavier than $\bar{b}$.

Let's identify each of these particles. Mass in GeV/c^2

γ photon mass:0 charge:0
e^- electron mass:0.000511
μ^+ antimuon mass:0.106

W^+ W boson mass:80.39 charge:+1
t top quark mass:173.1 charge:+2/3
$\bar{b}$ anti-bottom quark mass:4.18 charge: +1/3

Z^0 Z Boson mass:91.19

b bottom quark mass:4.18 charge: -1/3

W^- W boson mass:80.39 charge:-1
ν_e electron neutrino mass:small, charge:0

τ^- tau mass:1.777 charge:-1
τ^+ tau mass:1.777 charge:+1

c charm quark mass:1.28 charge:+2/3

$\bar{s}$ antistrange quark mass: 0.1 charge:+1/3

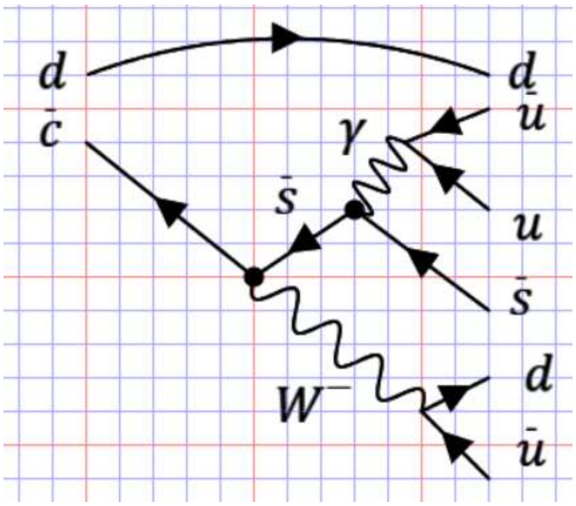
▶ Q2

(a) charge violation -1 to -2.

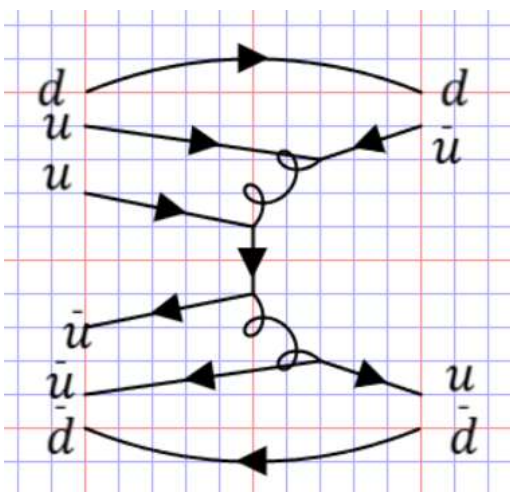
(b) Baryon number violation. 1 to 0

(c) This fails due to lepton flavor. The neutral pion has no lepton flavor, so there is a net gain of one -1 muon flavor.

(d) Valid assuming we can get an extra $u\overline{u}$. I didn't see it in the PDG but I'll make an attempt at a feynman diagram.
Overview: $d\overline{c} = \overline{s} + W^- + d = u\overline{s} + \overline{u}d + \overline{u}d$. That virtual photon is doing some heavy lifting



(e) This one works. Since the π^+ pion is $u\overline{d}$ and the proton is uud, there is a $u\overline{u}$ annihilation and the remaining quarks are split up into their pions. The annihilation creates virtual particles (gluons) which the remaining particles absorb. Gluons are necessary to keep the chromodynamics in order. Baryon number is conserved 1 + (-1)



(f) Lepton flavor violation. Also, where do the quarks go? Baryon number violation

Hadron descriptions

Ω^- sss 1.6 GeV/c^2
Ξ^- dss 1.3 GeV/c^2
π^- $\overline{u}d$ .14 GeV/c^2

Σ^+ uus 1.2 Gev/c^2
π^0 $u\overline{u}$ or $d\overline{d}$ .13 GeV/c^2

$D^- d\overline{c}$ 1.9 GeV/c^2
$K^+ u\overline{s}$ 0.49 GeV/c^2

▶ Q3

This question asks what the odds are that helium atoms hit gold atoms and scatter at a $45\degree$ angle. Hyperphysics has a pretty good walkthrough of this problem

The scattering of alpha particles from nuclei can be modeled from the Coulomb force and treated as an orbit. The scattering process can be treated statistically in terms of the cross-section for interaction with a nucleus which is considered to be a point charge Ze. For a detector at a specific angle with respect to the incident beam, the number of particles per unit area striking the detector is given by the Rutherford formula:

$$N(\theta) = \frac{N_i n L Z^2 k^2 e^4}{4r^2 KE^2 \sin^4(\theta/2)}$$

$N_i =$ *number of incident alpha particles*
$n =$ *atoms per unit volume in target*
$L =$ *thickness of target*
$Z =$ *atomic number of target*
$e =$ *electron charge*
$k =$ *Coulomb's constant*
$r =$ *target-to-detector distance*
$KE =$ *kinetic energy of alpha*
$\theta =$ *scattering angle*

Since this is the rate per unit area, we can either assume the angle is constant across the 1cm x 1cm detector, or do some calculus. I choose the former.

We'll have $N(\theta)$ calculate the rate of particles per unit area rather than the count. Then we have

$$\text{gold molar mass} = 196.967\ g/mol$$
$$19.7\ g/cm^3\ /\ 196.967\ g/mol\ =\ 0.1 mol/cm^3$$
$$n = 0.1 * 6.023e23\ \text{atoms}/cm^3$$

In [38]:
```
from scipy.constants import e, epsilon_0, pi, N_A
from numpy import sin

Ni = 1e5
n = 19.7/196.967*N_A #atoms / cm3
L = 0.1 # cm
Z = 79
k = 1/(4*pi*epsilon_0)
r = 100 # cm
KE = 10 * e * 1e6 #MeV to J
theta = pi/4

N = Ni * n * L * Z**2 * k**2 * e**4 / ( 4 * r**2 * KE**2 * (sin(theta/2))**4 )
N
```

Out[38]:
```
9.085792346300234e-05
```

That's much smaller than one. Maybe a flux of 10^5 isn't really a big number. Since our unit area is 1cm x 1cm, this is also the rate which the detector sees. It comes out to one particle every ~3 hours. This blows up for $\theta = 0$

▶ Q4

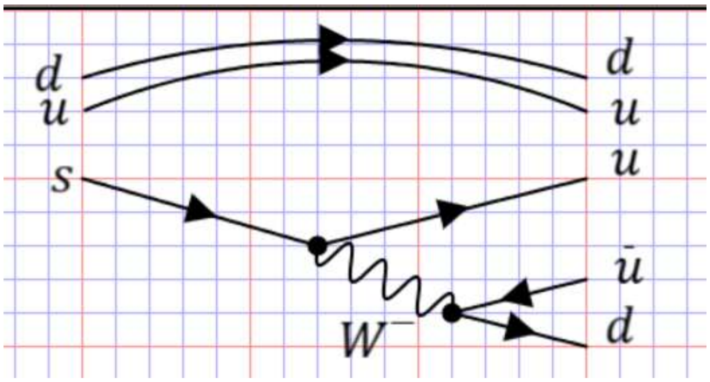
A) Let's examine the quark contents of each:

$$\Lambda : uds$$
$$p : uud$$
$$\pi^- : \overline{u}d$$

This is allowed if a weak interaction causes s to decay into u

$$s \rightarrow u + W^-$$
$$W^- \rightarrow \overline{u}d$$

Here is the Feynman diagram

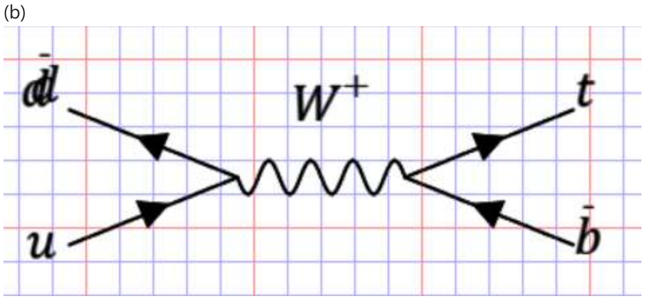


Also the rest mass of s should be enough to facilitate conservation of energy for inputs/outputs $E_s > E_p + E_{\pi^-}$

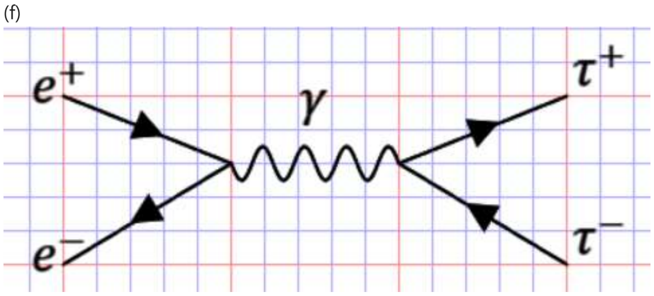
The second decay $\Lambda^0 \rightarrow \pi^+ + \pi^-$ violates baryon number. Protons are baryons but π aren't.

B) Energy violations can be solved if momentum frames are changed. This allows for (b) and (h) to occur, and helps with (f). We'll convert the beginning particles to virtual particles and have some incoming momentum on some particles with mass. This way, momentum can be converted to mass for the larger particles. Note that free-hanging quarks aren't allowed, so there would have to be even more happening after (b) and (h) to absorb the new quarks.

(b)



(f)



(h) B^+ decay