EXERCISE 1

Answers:

1. Probably 13. You can discuss whether all 13 are parallel, but bear in mind that this is physics and there will be a small spread in beam momenta (~1%).
2. Bottom to top.
3. Yes – they are the small spiral tracks turning to the left in the magnetic field..
4. The magnetic fields points out of the paper/screen (use the Lorentz-law in vector-form).
5. One (in the lower part of the image).
6. Three particles.
7. One negatively charged particle because it is curving in the same direction as the electrons. It is the track furthest to the right after the collision. One positively charged particle because it is curving in the opposite direction. It is the track furthest to the left after the collision. A neutral particle also results from the collision. It does not leave a track but we can see the tracks of the products into which it decays.
8. Using the charge conservation law, we can determine the charge of the beam tracks. We see one negative, one positive and one neutral particle emerge from the collision. This means the total charge after the collision is 0, and therefore the total charge before the collision must also be zero. Because the target is a proton, the charge of the beam must be negative.
9. There are no kinks.
10. One – the decay of the neutral particle (a vee) from the initial collision.
11. Two.
12. The track on the right curves in the opposite direction to that of the electron spirals, so the particle making the track must be positive. The track on the left curls the other way, so that particle must be negative. We could also have used the charge conservation law in the last step.
13. The positively charged one – its track bends the most ($p = Bqr$)

    Because the track is so dark it means the particle is losing much more energy per centimetre, which tells us it is moving much more slowly than the other particles. Low momentum coupled to low speed would suggest a large mass. Such tracks are readily recognized as protons.

What is the vee?

Since the tracks from the vee don't give any clues (a kink, for example), it is not possible to say more from a scan (visual inspection). We are left then with three possibilities:

1. $K^0 \rightarrow \pi^+ + \pi^-$
2. $\Lambda \rightarrow p^+ + \pi^-$
3. $\overline{\Lambda} \rightarrow \overline{p} + \pi^+$

To make progress we need to use the measured momenta and try all possible mass combinations to see if any give an "effective mass" (mass from now on) close to that of the K^0, Λ, or $\overline{\Lambda}$.

Track	p_x (GeV/c)	p_y (GeV/c)	p_z (GeV/c)
Negative	2.80879	-0.51130	0.45166
Positive	0.7638	0.04410	0.04419

In the first case the masses of the two pions are equal (m=0.139 GeV/c^2) and the energy of each one can be calculated with the relation (click here):

$$E^2 = \left(p_x^2 + p_y^2 + p_z^2\right) \cdot c^2 + m^2 \cdot c^4 \qquad (1)$$

Assuming that energy and momentum are conserved in the decay we can calculate the momentum and energy of the K^0 hypothesized:

Possible particle	p_x (GeV/c)	p_y (GeV/c)	p_z (GeV/c)	Mass (GeV/c²)	E (GeV)
π^-	2.80879	-0.51130	0.45166	0.13957	2.89381
π^+	0.7638	0.04410	0.04419	0.13957	0.77895
Sum	3.57259	-0.46720	0.49579		3.67277

Using equation (1) we can calculate its mass. In this case we get m= 0.511 GeV/c², which corresponds well with the mass of the K^0 (0.498 GeV/c²).

In the second and the third case the calculations are the same; the only difference is the masses of the particles from the decay. The results obtained in these cases are shown in the tables below:

Possible particle	p_x (GeV/c)	p_y (GeV/c)	p_z (GeV/c)	Mass (GeV/c²)	E (GeV)
π^-	2.80879	-0.51130	0.45166	0.13957	2.89381
p	0.7638	0.04410	0.04419	0.93827	1.21146
Sum	3.57259	-0.46720	0.49579		4.10527

The mass of the initial particle is, in this case, m= 1.904 GeV/c², which does not correspond well with the mass of the Λ (1.116 GeV/c²).

Possible particle	p_x (GeV/c)	p_y (GeV/c)	p_z (GeV/c)	Mass (GeV/c²)	E (GeV)
π^+	2.80879	-0.51130	0.45166	0.13957	2.89381
$\bar{p}$	0.7638	0.04410	0.04419	0.93827	1.21146
Sum	3.57259	-0.46720	0.49579		4.10527

The mass of the initial particle is, in this case, m= 1.904 GeV/c², which does not correspond well with the mass of the $\overline{\Lambda}$ (1.116 GeV/c²).

From this we conclude that the decaying particle is a K^0.

Are there any particles that have escaped the bubble chamber undetected?

We can check this by checking energy and momentum conservation.

The final measurement for this collision is as follows:

Particle	p_x (GeV/c)	p_y (GeV/c)	p_z (GeV/c)	Mass (GeV/c²)	E (GeV)
K⁻ (beam)	8.26131	-0.15642	0.0132	0.49368	8.27753
p (target)	0	0	0	0.93827	0.93828
Sum (initial)	8.26131	-0.15642	0.0132		9.21581
π^-	4.49326	0.73621	-0.51122	0.13957	4.58391
p	0.32496	-0.45360	0.04282	0.93827	1.09250
K^0	3.44322	-0.43912	0.48159	0.49767	3.53952
Sum (final)	8.26144	-0.15651	0.01319		9.21593

An inspection of the initial and final state shows that energy and momentum are conserved (within errors), and so there are no missing particles. In summary, the reaction is:

$$K^- p \to K^0 \pi^- p \ \text{ followed by } \ K^0 \to \pi^+ \pi^-$$

Click here for animation of this event.

Here is a question you might have asked:

How has the 4.6 GeV negative track from the collision been identified as a pion? After all, it is highly relativistic ($p^2 c^2 > m^2 c^4$ for π^-, K^- and $\bar{p}$ masses) and leaves no clue such as a decay or an interaction.

Use has been made of the laws of conservation of baryon number (this rejects the $\bar{p}$ possibility) and strangeness (this rejects the K^- possibility).

(Strangeness is a quantum number which is conserved in strong interactions, but not in weak interactions – and is outside the scope of this bubble chamber website. However, if despite this warning you would like a first look at how strangeness conservation works, click here.)