

Elementary particles and fundamental forces

- Upper secondary school -

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Exercise 1.

According to the current theories of particle physics we consider the following particles to be elementary: the quarks, leptons and interaction bosons. In table 1 one can see listed all the particles with their properties and their names. For every quark and lepton in the table there is a partner particle called anti-particle which has the same properties but with the electric charge reversed. (For instance the up quark is denoted by u and its antiparticle by $\bar{u}$).

In the following we will use the name of quark both to designate the quarks and the anti-quarks. Quarks can participate in combinations of two or three to create composed particles obeying the rule that the total charge to be an entire number. The "top" quark is an exception and doesn't participate in any combinations since it has a very short lifetime. The combinations of two quarks are known as *mesons* and the combinations of three quarks are called *baryons*. All particles made of quarks are also called *hadrons*.

With these information, answer the following questions.

	mass → $\approx 2.3 \text{ MeV}/c^2$ charge → $2/3$ spin → $1/2$ u up	mass → $\approx 1.275 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ c charm	mass → $\approx 173.07 \text{ GeV}/c^2$ charge → $2/3$ spin → $1/2$ t top	mass → 0 charge → 0 spin → 1 g gluon	mass → $\approx 126 \text{ GeV}/c^2$ charge → 0 spin → 0 H Higgs boson
QUARKS	mass → $\approx 4.8 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ d down	mass → $\approx 95 \text{ MeV}/c^2$ charge → $-1/3$ spin → $1/2$ s strange	mass → $\approx 4.18 \text{ GeV}/c^2$ charge → $-1/3$ spin → $1/2$ b bottom	mass → 0 charge → 0 spin → 1 γ photon	
	mass → $0.511 \text{ MeV}/c^2$ charge → -1 spin → $1/2$ e electron	mass → $105.7 \text{ MeV}/c^2$ charge → -1 spin → $1/2$ μ muon	mass → $1.777 \text{ GeV}/c^2$ charge → -1 spin → $1/2$ τ tau	mass → $91.2 \text{ GeV}/c^2$ charge → 0 spin → 1 Z Z boson	
LEPTONS	mass → $< 2.2 \text{ eV}/c^2$ charge → 0 spin → $1/2$ ν_e electron neutrino	mass → $< 0.17 \text{ MeV}/c^2$ charge → 0 spin → $1/2$ ν_μ muon neutrino	mass → $< 15.5 \text{ MeV}/c^2$ charge → 0 spin → $1/2$ ν_τ tau neutrino	mass → $80.4 \text{ GeV}/c^2$ charge → ± 1 spin → 1 W W boson	GAUGE BOSONS

Figure 1: The Standard Model table of elementary particles. There are three types of particles: **quarks** și **leptons**, **interaction bosons**

1. Compute the total electrical charge of the following combinations of quarks.

- | | | |
|--------------------------------------|------------------------------------|--|
| a. uud - proton,
_____ | b. udd - neutron,
_____ | c. $u\bar{d}$ - π meson ,
_____ |
| d. $s\bar{d}$ - K meson ,
_____ | e. $c\bar{d}$ - D meson
_____ | |

2. Fill out the composition and the charge of the anti-particle of the example from above

- | | | |
|------------------------------------|------------------------------------|--------------------------------------|
| a. anti-proton
_____, ____ | b. anti-neutron
_____, ____ | c. anti-meson π^+
_____, ____ |
| d. anti-meson K^+
_____, ____ | e. anti-meson D^0
_____, ____ | |

3. Compute the total number of combinations that can be formed from two quarks and select the right answer from below.

- | | | |
|-------|--------|-------|
| a. 12 | b. 100 | c. 36 |
| d. 25 | e. 84 | |

4. Compute the total number of combinations that can be formed from three quarks and select the right answer from below.

- | | | |
|--------|--------|--------|
| a. 21 | b. 62 | c. 125 |
| d. 250 | e. 168 | |

5. Which elementary particle is the most abundant in the human organism? Start from the chemical composition of the human body and write down in descending order the three most abundant elementary particles.

- a) _____
- b) _____
- c) _____

Exercise 2.

1. If the nucleus of an atom would measure 1 cm, what would be the total dimension of the atom?
 - a. as a sheet of paper
 - b. as a football stadium
 - c. as large as the Bucharest city
 - d. as five football stadiums
 - e. as large as the whole universe

2. What is the total distance travelled by the protons within LHC ring in 10 hours? Assume that the speed of the protons is equal to the speed of light. Which of the following distances is closer to the value obtained?
 - a. The distance between Earth and Sun back and forth
 - b. The distance between Earth and Neptun back and forth
 - c. The distance between London and Paris
 - d. The distance around the Earth

3. At LHC the protons are accelerated in bunches of protons, the average density of a bunch is 10^{11} protons. All the bunches that are in the LHC at a given time form a beam, a beam has around 2800 bunches. When the experiment is finished the beam is extracted from the ring and dumped in a block of concrete foreseen for this purpose. Calculate the energy of the beam given that the energy of a proton is 7 TeV, i.e. $7 \cdot 10^{12}$ eV. The electron-volt (eV) is unit used to express the energy of the particles it is equivalent to $1 \text{ eV} = 1,602 \cdot 10^{-19}$ Joules.
 Compare this energy with the energies from the following examples and pick the one which is closer to the one calculated.
 - a. a speeding TGV train
 - b. a fly
 - c. an Airbus palne
 - d. a bullet fired by a gun

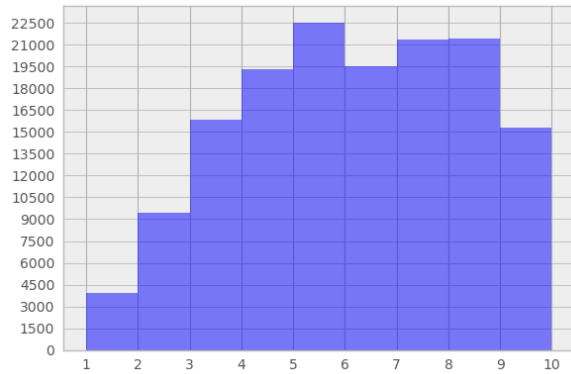
Indication: for each of the variants consider the tipical values for the masses and speeds.

Exercise 3.

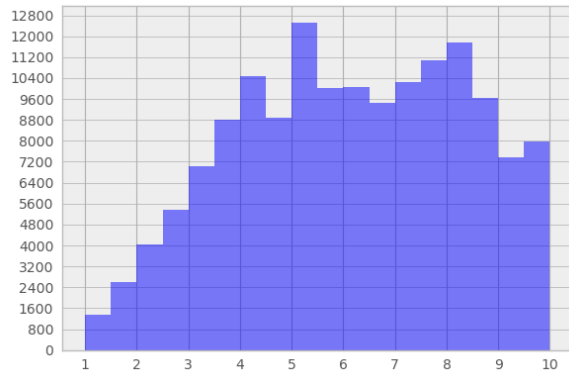
A histogram is a common type of plots in the experimental physics. On OX axis we put the values for the quantity of interest and on OY we note the number of times a certain value has appeared after repeated measuremets.

To get acustom with this quantity we will plot on a histogram the marks from the exams at mathematics for the last grade of the lower secondary school. The data is for the national exam in year 2016 in Romania. On the OX axis are the marks from 0 to 10, 10 is the best mark. On the OY axis we note how many students had a certain mark. The histogram can be seen in the figure 2a. A bin is the interval on the OX axis for which we assign a single value on the OY axis. In the histogram 2a we have 10 bins of dimension 1. Examples of bins are $(0, 1), \dots (4, 5), (5, 6), \dots (9, 10)$.

1. Using the information from the figure 2a, extract the following quantities:



(a) The marks are represented in bins of unit 1.



(b) The marks are represented in bins of unit 0.5.

Figure 2: Histogram plots for the math exams in 2016 in Romania.

- a. the number of students which gave the exam, _____
- b. average mark, _____
- c. the most frequent mark assigned, _____
- d. the lowest mark assigned, _____
- e. the highest mark assigned, _____

2. The same information about the marks can be represented in a plot with smaller bins. For instance, the same data is presented in figure 2b as a histogram with bins of 0.5. For this case extract the same quantities as before.

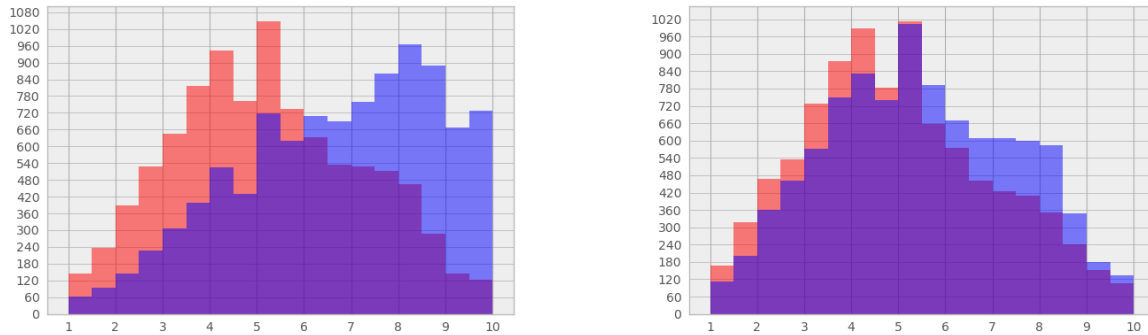
- a. the number of students which gave the exam, _____
- b. the average mark, _____
- c. the most frequent mark assigned, _____
- d. the lowest mark assigned, _____
- e. the highest mark assigned, _____

Observations: the number of students giving the exam is the same in both cases, the average mark is different being higher in the second case, why?

3. Compare the histograms from the following examples¹

- a. In figure 3a we have plotted two distributions of marks from the math exam a) of the students from the urban areas (blue) b) of the students from the rural areas (red)². How do the histograms differ, comment the results.
- b. In figure 3b we have plotted two distributions of marks from the math exam a) of the girls (blue) b) of the boys (red). How do the histograms differ, comment the results.

¹For making things easier we considered the same number of students in each category.

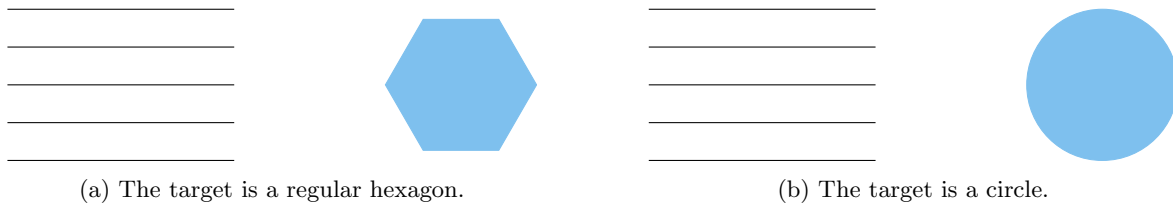


(a) The marks in the urban areas (blue) and in the rural areas (red). (b) The marks of the girls with blue and of the boys with red.

Figure 3: Comparison of the marks for math exam of different groups of students.

Exercise 4.

The typical experiments in particle physics are collisions experiments. To understand better one can simulate them at macroscopic scale. Let's have a fix target in the horizontal plane on which we throw balls in OX direction. Follow the direction of the balls after hitting the target and registrate the deflection angles. The exercise asks to draw the histograms for the two targets in the figure 4, when the beam contains 1000 balls, uniformly distributed on the target cross section.



(a) The target is a regular hexagon.

(b) The target is a circle.

Figure 4: The scattering of a beam of particles on targets with different shapes.

1. The target is a regular hexagon like in the figure 4a. Draw the histogram in the figure 5.
2. The target is a circle in the figure 4b. Draw the histogram in the figure 6.

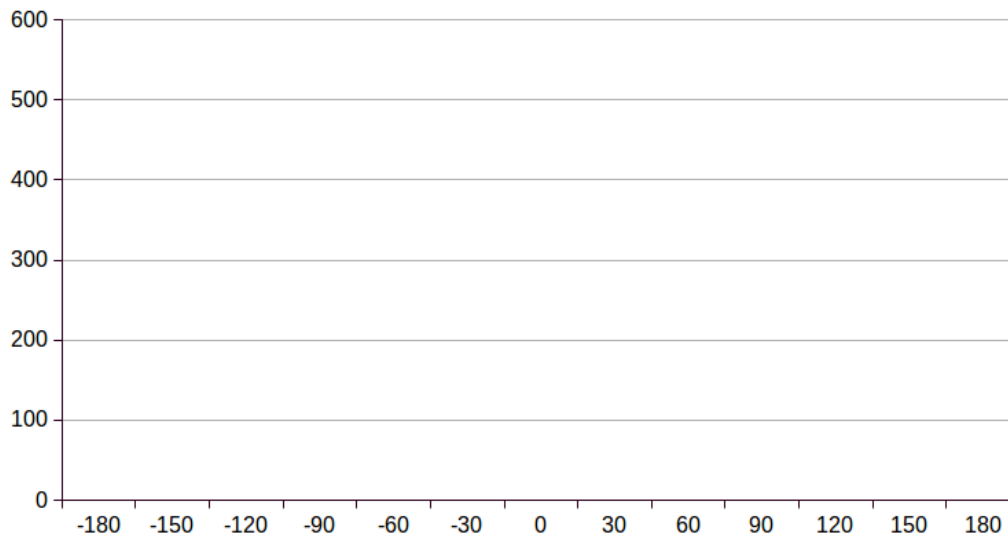


Figure 5: Draw the histogram of the scattering angles when the target is a regular hexagon.

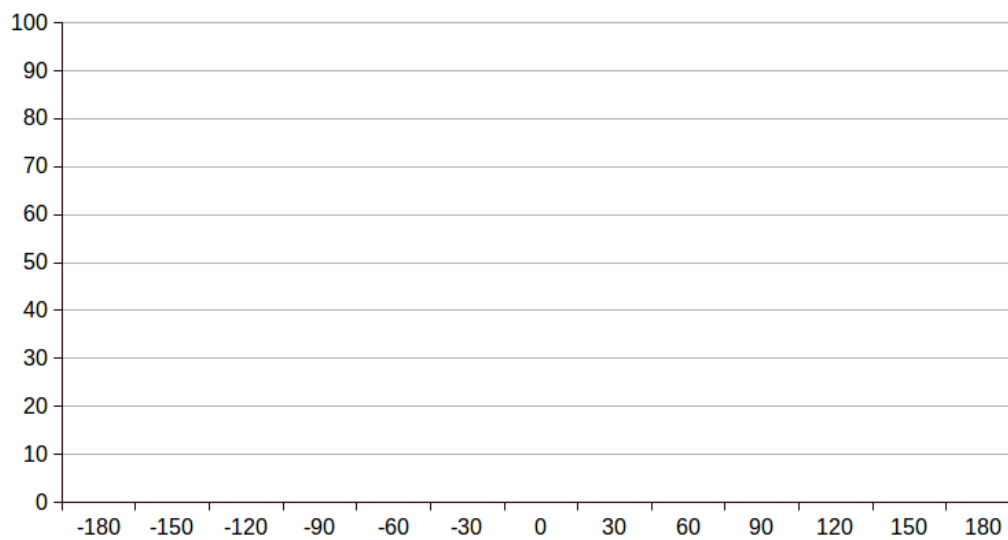


Figure 6: Draw the histogram of the scattering angles when the target has the shape of a circle.



Figure 7: Collision experiment, throwing a projectile ball toward a target linear target made of identical poles distributed non-uniformly on a row of length L .

Exercise 5.

The following practical activity illustrates the principle of indirect measurements in experimental particle physics.

A number of balls (obstacles) of equal sizes are arranged in a row on a floor see picture 7. The balls simulate the atoms/nuclei from a thin foil of a material and play the role of the target. Their arrangement can be non-uniform but the total length L of the row should be known. It is also known the total number of balls in the target N .

Throw the projectile balls toward the target from a distance of 3 - 5 meters and record if the projectile hit a ball in the target or not. Repeat the experience over 100 times, maintaining the same distance. Let's denote with N_A the total number of throws, and with n_c the number of collisions.

1. Do the experiment in the class, from the values obtained for N_A and n_c compute the radius R of the balls forming the target.
2. Do a direct measurement of the radius of the ball from the target using a ruler and compare it with the value obtained from the indirect measurement.
3. Calculate the absolute error and the relative error of the result in the indirect measurement. How do the errors modify if the experiment is repeated with a projectile ball of a different dimension. de dimensiune diferită.

Exercise 6.

Follow the instructions from LHCb Masterclass website [1].

References

- [1] LHCb Collaboration. Lhcb international masterclasses. lhcb-public.web.cern.ch/lhcb-public/en/LHCb-outreach/masterclasses/en/.