

STUDY OF ELECTRICAL CONDUCTION OF THE ELECTROLYTES USING THE RASPBERRY PI

BOGDAN GHERASIM¹, VLAD-ANDREI ANTOHE^{1,2}, OVIDIU TOMA¹, CRISTINA MIRON^{1,*},
ȘTEFAN ANTOHE^{1,3,*}

¹ University of Bucharest, Faculty of Physics, Atomistilor Street 405, 077125, Bucharest, Romania

² Institute of Condensed Matter and Nanosciences (IMCN), Université Catholique de Louvain
(UCLouvain), Place Croix du Sud 1, B-1348 Louvain-la-Neuve, Belgium

³ Academy of Romanian Scientists (AOSR), Ilfov Street 3, 050045, Bucharest, Romania

* Corresponding authors: cristina.miron@fizica.unibuc.ro, santohe@solid.fizica.unibuc.ro

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Abstract. Pure water does not conduct electricity, but if we dissolve a salt or an acid in it, then the resulting ions can provide electrical conductivity. For teaching purposes, we can study this electrical conductivity using a Raspberry Pi single-board computer connected with a series of sensors. Thus, we get suggestive graphics that illustrate the physical processes taking place during the electric conduction in an electrolyte, and we can project them on a smart board to be available to the whole class.

Key words: Raspberry Pi, electrolytes, electrical conductivity, physics education.

1. INTRODUCTION

Physics is a discipline fundamentally grounded in experimental methodology, which underscores the integral role of didactic experiments in its instruction. Advancements in physics education have highlighted the significance of incorporating school-based experimental activities. The integration of digitized experimental practices may substantially enhance the effectiveness and appeal of physics instruction [1–5].

When we teach electricity, we also tell students about the electrical conductivity in various materials. In solids, the electric current is generated by the oriented movement of electrons in the energy band called the conduction band. But in the liquids the transport of the charge carriers are generally the ions resulting from dissociation of the molecules of soluble substances, then the notion of conduction band for electrons is not appropriate. In this case, the electrical conduction mechanism is different.

Pure water does not conduct electricity. The water molecule contains only covalent bonds. The number of positive and negative charges in this molecule is

equal, so the net electric charge is zero and it has no conduction band through which the electrons could move. But things change if we introduce a salt or other ionic compound into the water. The water molecules interact with the ions in that salt and as a result of this interaction the salt dissociates into positive ions and negative ions that can move freely through the aqueous solution. Such a solution is called an electrolyte. For example, if we put (NaCl) salt in water, it dissociates into positive ions (Na^+) and negative ions (Cl^-). If we introduce two electrodes into this solution and apply an electric voltage to the two electrodes, then the positive ions will be attracted to the negative electrode and the negative ions will be attracted to the positive electrode. The movement of ions through the solution creates an electric current. The local form of Ohm's law, valid for example in the case of the conducting medium, i.e., $\vec{j} = \sigma \vec{E}$ is still the same [6], but in this case, the conductivity is related to the concentration of ions and their mobility [7]. The mobility depends on the type of ions, the concentration and the temperature.

Didactic experiments play an important role in teaching physics [8] and the modern trend is the digitalization of education [9]. In this paper we will present a series of digital didactic experiments related to the electrical conduction through electrolytes. For this purpose, we used a single Raspberry Pi [10-13] and several sensors. All the programs we used were written in Python, the main programming language for Raspberry Pi [14].

Another phenomenon that occurs when we insert an electrode into an electrolyte is that an electrode potential appears at the contact surface between the electrodes and the electrolyte. This electrode potential can influence our measurements. There are few methods to limit the influence of the electrode potential. The best method is to use hydrogen electrodes, which have an electrode potential equal to zero. But these electrodes are very expensive and cannot be found in ordinary school laboratories. The second method is to use electrodes made of the same material at both the positive and negative poles. In this way, the electrode potentials are equal, and the potential difference is zero. This method is not perfect, but it is much cheaper, and it is precise enough for didactic experiments. We used this method in our experiments.

We used NaCl solutions in water because these substances are not dangerous for students. After the microscopic approach of the electrical conduction through the electrolytes, from the theoretical point of view, we carried out the following experiments: (i) the dependence of the current through the electrolyte as a function of the applied voltage between the electrodes (I-U) characteristics, (ii) the dependence of the current through the electrolyte on the distance between the electrodes; (iii) the dependence of the current through the electrolyte on the concentration; (iv) the dependence of the current through the electrolyte on the temperature.

2. MICROSCOPIC APPROACH OF THE ELECTRICAL CONDUCTIVITY OF ELECTROLYTES

In the absence of an external electric field, the ions in the electrolytes perform a movement of thermal agitation, so the resulting current will be equal to zero. In the presence of the electric field, the positive ions of mass m_+ and charge q_+ will move in the direction of the field with the velocity v_+ , while the negative ions of mass m_- and the charge q_- will move in the opposite direction to the electric field with velocity v_- . In a treatment of classical mechanics, the ions moving within electrolyte are subjected in addition to the electric force, also of the action of a friction force with the electrolyte, proportional to their speed, resulting the following equations of motion for the two types of ions [6]:

$$\begin{cases} m_+ \vec{a}_+ = q_+ \vec{E} - k_+ \vec{v}_+ \\ m_- \vec{a}_- = q_- \vec{E} - k_- \vec{v}_- \end{cases} \quad (1)$$

Under conditions of uniform movement for the two ions, equations (1) lead to:

$$\begin{cases} \vec{a}_+ = 0 \Rightarrow \vec{v}_+ = \frac{q_+ \vec{E}}{k_+} = \mu_+ \vec{E} \\ \vec{a}_- = 0 \Rightarrow \vec{v}_- = \frac{q_- \vec{E}}{k_-} = \mu_- \vec{E} \end{cases} \quad (2)$$

It is noticed that the velocities of the positive and negative ions also called drift speeds are proportional to the intensity of the electric field, the proportionality coefficients being the mobilities of the positive and negative ions μ_+ and μ_- , respectively. The density of the electric current that arises by the displacement in the electric field of the positive and negative ions will be:

$$\vec{j} = \vec{j}_+ + \vec{j}_- = q_+ n_+ \vec{v}_+ + q_- n_- \vec{v}_- \quad (3)$$

where n_+ and n_- are the concentrations of the positive and negative ions in the solution, respectively. Defining $\alpha = \frac{n_+}{n_0} = \frac{n_-}{n_0}$, the ‘*dissociation coefficient*’ (which represents the number of dissociated molecules in the volume unit relative to the number of molecules n_0 in the volume unit of the dissolved substance), i.e., relation (3) becomes:

$$\vec{j} = \alpha n_0 (q_+ \vec{v}_+ + q_- \vec{v}_-) = q \alpha n_0 (\vec{v}_+ + \vec{v}_-) \quad (4)$$

It was considered $q_+ = q_- = q$. The dissociation coefficient takes values between 0 and 1 ($\alpha = 1$ when all molecules are dissociated, i.e., $n_+ = n_- = n_0$, while $\alpha = 0$ when no molecule is dissociated, i.e., $n_+ = n_- = 0$). The intensity of the electronic current in the external circuit is determined by the intensity of the ionic

current in the electrolytic solution. Indeed, as it has been shown before, the negative ions go to the anode where they neutralize, their charge (electrons) passing into the external circuit so that the electronic current being equal to the an ionic one. Similarly, electrons from the external circuit come to the cathode, which allows the neutralization of positive ions (cations) that are discharged at the cathode. Introducing the quantity $\eta = \frac{n_0}{N'}$, called '*equivalent concentration*', representing the number of gram equivalents in the volume unit, it results for the electric current density the relationship [7]:

$$\vec{j} = \alpha N' q \eta (\vec{v}_+ + \vec{v}_-) \quad (5)$$

in which n_0 is the concentration of molecules in the solution and N' is the number of molecules in a gram equivalent. But $N'q$ representing the number of molecules in a gram equivalent, it follows that $N'q$ is exactly the electric charge transported through the electrolyte to deposit one gram equivalent at electrode, so it is in other words precisely the Faraday's number. With this, the current density can be re-written as:

$$\vec{j} = F \alpha \eta (\vec{v}_+ + \vec{v}_-) \quad (6)$$

or taking into account the relationships (2), for the definition of drift velocities, it results:

$$\vec{j} = F \alpha \eta (\mu_+ + \mu_-) \vec{E} = \sigma \vec{E}; \quad \sigma = F \alpha \eta (\mu_+ + \mu_-) \quad (7)$$

For a given solution, the value of $F \alpha \eta (\mu_+ + \mu_-)$ is constant and taking into account the Ohm's law in its local form, i.e., $\vec{j} = \sigma \vec{E}$, this coefficient is effectively the electrolytic conductivity. The notion of *equivalent conductivity*, i.e., $\Lambda = \frac{\sigma}{\eta}$, defined as the ratio between the conductivity of the electrolyte and its equivalent concentration, can also be introduced. With this, the relation (7) describing the electrolyte' conductivity becomes:

$$\Lambda = \frac{\sigma}{\eta} = F \alpha (\mu_+ + \mu_-) \quad (8)$$

In the case of weak solutions (highly diluted), when practically all the molecules of the dissolved substance are dissociated ($\alpha = 1$), it results $\Lambda_\infty = F(\mu_+ + \mu_-)$. So, for solutions, at which $0 < \alpha < 1$, by determining Λ the dissociation coefficient α can be determined [7]:

$$\alpha = \frac{\Lambda}{\Lambda_\infty} \quad (9)$$

Λ and σ depend both on the concentration of the dissolved substance and the value of the dissociation coefficient (α).

For most substances, electrical conductivity (σ) initially increases with concentration until it reaches a maximum. Then, at high concentrations, it decreases due to the decrease in the dissociation coefficient, as confirmed by the experimental part.

3. EXPERIMENTAL PROCEDURES AND RESULTS

For our study, we used a didactic electrolysis cell that allows changing the distance between the electrodes in steps of 12 mm. When we insert an electrode into an electrolyte, an electrode potential appears [15]. To compensate for the electrode potentials, we used electrodes made of the same material at both the anode and the cathode. We also used an adjustable voltage source.

The data processing unit is a Raspberry Pi 4. This is a computer built on a single board, but what makes it really useful is the fact that it has 40 GPIO pins to which we can connect various sensors or other devices [16-17]. This feature helps us perform educational physics experiments using Raspberry Pi and sensors connected to the GPIO pins [18-22].

For our study we used an ACS712 current sensor for measuring the current through the electrolysis cell and for measuring the voltage we used a voltage sensor. Both sensors are analog and therefore, to connect them to the Raspberry Pi we need to convert the analog signal to a digital one. For our experiment we used the SparkFun Qwiic 12 Bit ADC - 4 Channel analog-to-digital converter (ADS1015) which takes the analog signal in the form of a voltage between 0 and 3.3V and converts this voltage into a number which is then transmitted through a I2C connection to the Raspberry Pi. The Raspberry Pi collects and processes the data transmitted by the sensors. For this purpose, we wrote several programs in the Python language, one for each experiment.

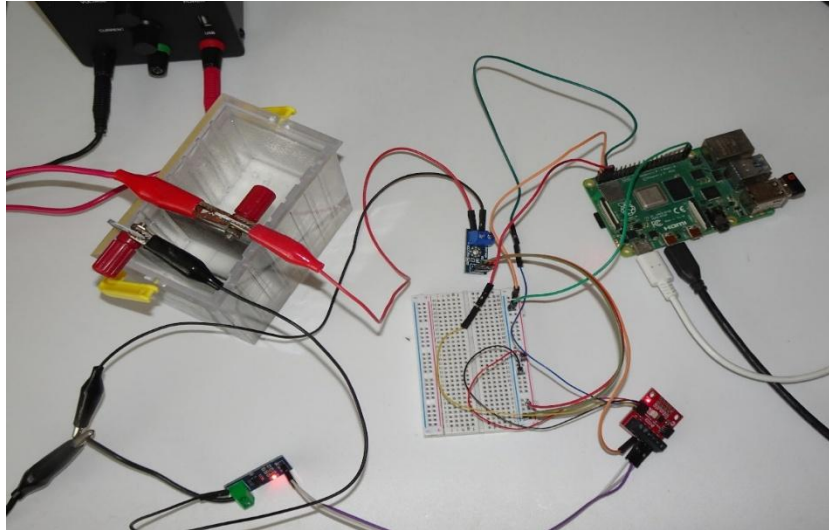


Fig. 1 – Setup used for the study of electrical conduction in electrolytes. The full color version may be accessed at <https://rrp.nipne.ro>.

3.1. CURRENT-VOLTAGE CHARACTERISTIC

In the first experiment we plotted the current-voltage characteristics (I-U) of a 5% NaCl solution in water at room temperature. We connected the current sensor in series with the electrolysis cell and the voltage sensor in parallel, then connected both sensors to the analog inputs of the converter and the converter to pins 1, 3, 5 and 39 of the Raspberry Pi (1 for +3.3V, 3 for SDA, 5 for SCL and 39 for ground). We also used a breadboard to connect all the devices. The setup for the experiment can be seen in Figure 1. We used the following Python program for this experiment:

```
import matplotlib.pyplot as plt
import Adafruit_ADS1x15
import math
from time import sleep
adc = Adafruit_ADS1x15.ADS1115()
li=[]
lv=[]
tx=""
while tx=="":
    sleep(1)
    value = adc.read_adc(0, gain=1)
    vol = adc.read_adc(1, gain=1)
    ana = value*(4.096/32767)
```

```
amp=(10*ana-16.52)
volt=5*vol*(4.096/32767)
print(amp, volt)
li.append(amp)
lv.append(volt)
tx=input('For a new measurement press ENTER ')
plt.plot(lv, li, 'ro:')
plt.xlabel('U [V]')
plt.ylabel('I [A]')
plt.show()
exit
```

This program determines the values of voltage and current through the liquid, then plots the current versus voltage graph. We started the program and gradually changed the supply voltage of the electrolysis cell. The resulting plot is shown in Figure 2.

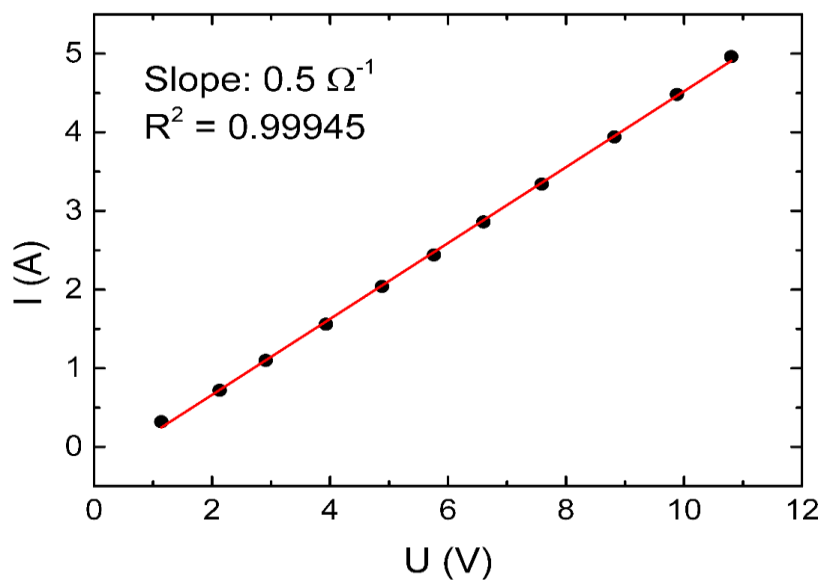


Fig. 2 – Current-Voltage (I-U) characteristic of 5% NaCl solution in water at room temperature. The experimental data were fitted by a linear regression, where R^2 denotes the coefficient of determination. The full color version may be accessed at <https://rrp.nipne.ro>.

In this graph we can see that the intensity of the current increases with the increase of the voltage applied to the electrodes with a fairly good linearity. The slope of this linear regression represents the conductance of the electrolyte (i.e.,

$1/R$). So, the resistance value of the electrolyte between the two electrodes, placed at a constant distance, is 2Ω .

3.2. VARIATION OF THE CURRENT AS A FUNCTION OF THE DISTANCE BETWEEN THE ELECTRODES

For the next experiment we used the same devices, but kept the voltage constant and varied the distance between the electrodes in steps of 1.2 cm. We used the following Python program:

```
import matplotlib.pyplot as plt
import Adafruit_ADS1x15
import math
from time import sleep
adc = Adafruit_ADS1x15.ADS1115()
li=[]
ld=[]
tx=""
while tx!="":
    di=input('Distance between electrodes in cm: d=')
    d=float(di)
    ld.append(d)
    sleep(1)
    value = adc.read_adc(0, gain=1)
    ana = value*(4.096/32767)
    amp=(10*ana-16.52)
    print(d, amp)
    li.append(amp)
    tx=input('For a new measurement press ENTER ')
plt.plot(ld, li, 'ro:')
plt.xlabel('d [cm]')
plt.ylabel('I [A]')
plt.show()
exit
```

The program measures the current for different values of the distance and then plots the graph of the current as a function of the distance between the electrodes. After performing the experiment, we obtained the graph shown in Figure 3.

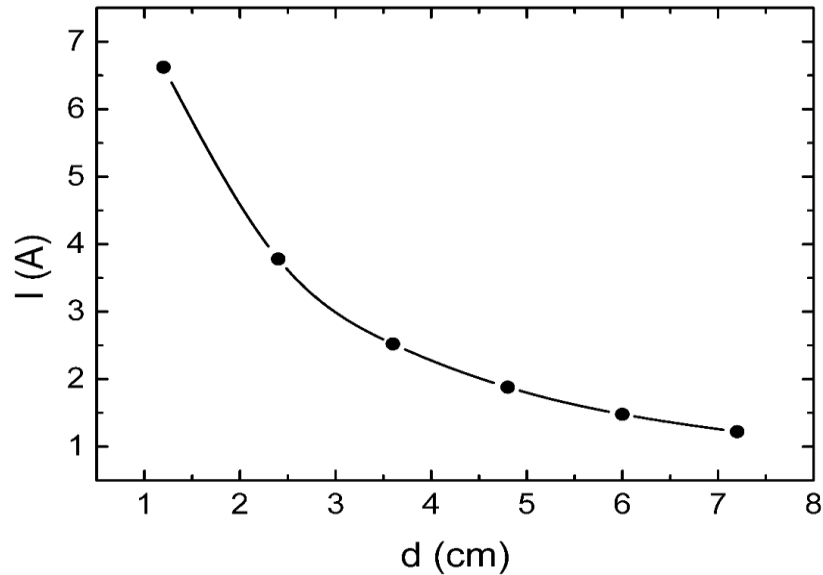


Fig. 3 – Dependence of the current through the electrolyte on the distance between the electrodes.

As expected, we observe that the intensity of the current decreases by increasing the distance between the electrodes. Considering that the voltage remained constant, this means that the resistance of the liquid increases when the distance between the electrodes increases, according with the conventional relation:

$$R = \frac{1}{\sigma} \frac{d}{S}$$

3.3. VARIATION OF THE CURRENT AS A FUNCTION OF CONCENTRATION

Another interesting experiment is related to the variation of the resistivity of an electrolyte as a function of ion concentration. For this experiment, we used another substance that we normally find in the kitchen: $\text{CH}_3\text{-COOH}$ (Acetic Acid). We used the same experimental device and we kept constant the voltage and the distance between the electrodes, but we poured solutions with different concentrations in turn into the electrolysis tank. For the 0% concentration we used distilled water and for the following we added different amounts of $\text{CH}_3\text{-COOH}$. Considering the nature of $\text{CH}_3\text{-COOH}$, we used a voltage of 30 V and the concentration was expressed in %. We used the following Python program:

```
from time import sleep
adc = Adafruit_ADS1x15.ADS1115()
lm=[]
```

```
li=[]
ld=[]
tx=""
while tx!="":
    di=input("The concentration in %: c=')
    d=float(di)
    ld.append(d)
    sleep(1)
    value = adc.read_adc(0, gain=1)
    ana = value*(4.096/32767)
    amp=(10*ana-16.52)
    print(d, amp)
    li.append(amp)
    tx=input('For a new measurement press ENTER ')
plt.plot(ld, li, 'ro:')
plt.xlabel('c [%]')
plt.ylabel('I [A]')
plt.show()
exit
```

The program measures the current through the electrolysis vessel for various concentration values and then plots the current versus concentration graph. We ran the program and got the graph from Figure 4.

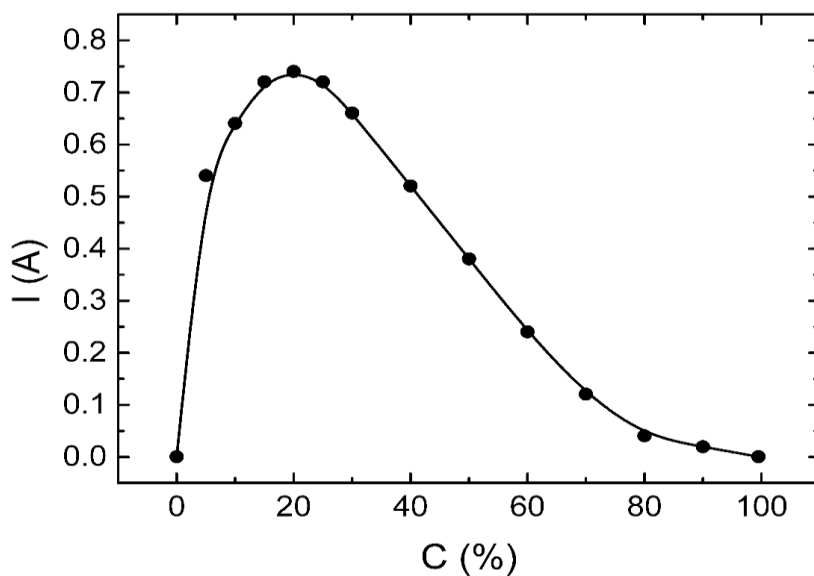


Fig. 4 – Dependence of the Current on the CH₃-COOH concentration.

From this graph we see that neither pure water nor pure $\text{CH}_3\text{-COOH}$ conducts electric current, but if we mix the two substances, the $\text{CH}_3\text{-COOH}$ molecule splits into ions and thus an electrical conductivity appears that depends on the number and mobility of the ions. At low concentration, the conductivity of the electrolyte increases with the concentration increasing due to more ions resulted from the acid molecules dissociation will participate to transport of the charge, but it reaches a maximum value to the concentration of about 25%. After this value the conductivity of the electrolyte decrease because the decreasing of the dissociation coefficient according with the equation (7). At a high dilution the dissociation coefficient is maximum $\alpha = 1$ and at a saturated solution the dissociation coefficient $\alpha \rightarrow 0$ according to the theory presented in the section 2.

3.4. VARIATION OF CURRENT THROUGH ELECTROLYTE AS A FUNCTION OF TEMPERATURE

We have seen that the ions present in the solution, are responsible for the electrical conduction of the electrolytes, and we want to see how this conduction changes as a function of their mobility. For this we studied the dependence of the electric current on the temperature of the electrolyte. We used a similar setup to the previous experiments, but added a DS18B20 waterproof temperature sensor that has an accuracy of 0.5 °C. This is a 1-wire interface sensor and so we connected it to pin 7 of the Raspberry Pi and the power supply, and then inserted it into the electrolysis cell. We used a NaCl solution with a concentration of 50 g/l which we heated to near boiling point and then poured into the electrolysis cell where it cooled gradually and we made several determinations at different temperatures. We used the following Python program:

```
import matplotlib.pyplot as plt
import Adafruit_ADS1x15
import glob
import time
adc = Adafruit_ADS1x15.ADS1115()
li=[]
lt=[]
tx=""
base_dir = '/sys/bus/w1/devices/'
device_folder = glob.glob(base_dir + '28*')[0]
device_file = device_folder + '/w1_slave'
def read_temp_raw():
    f = open(device_file, 'r')
```

```
lines = f.readlines()
f.close()
return lines
def read_temp():
lines = read_temp_raw()
while lines[0].strip()[-3:] != 'YES':
time.sleep(0.2)
lines = read_temp_raw()
equals_pos = lines[1].find('t=')
if equals_pos != -1:
temp_string = lines[1][equals_pos+2:]
temp_c = float(temp_string) / 1000.0
return temp_c
tx=""
while tx=="":
time.sleep(1)
value = adc.read_adc(0, gain=1)
ana = value*(4.096/32767)
amp=(10*ana-16.52)
t=read_temp()
print(t, amp)
li.append(amp)
lt.append(t)
tx=input('For a new measurement press ENTER ')
plt.plot(lt, li, 'ro:')
plt.xlabel('t [Celsius]')
plt.ylabel('I [A]')
plt.show()
```

The program takes several readings of current and temperature and then plots the current versus temperature graph. In order for the sensor and liquid to reach thermal equilibrium, readings are taken at intervals of the order of minutes. After performing the experiment, the graph in Figure 5 resulted.

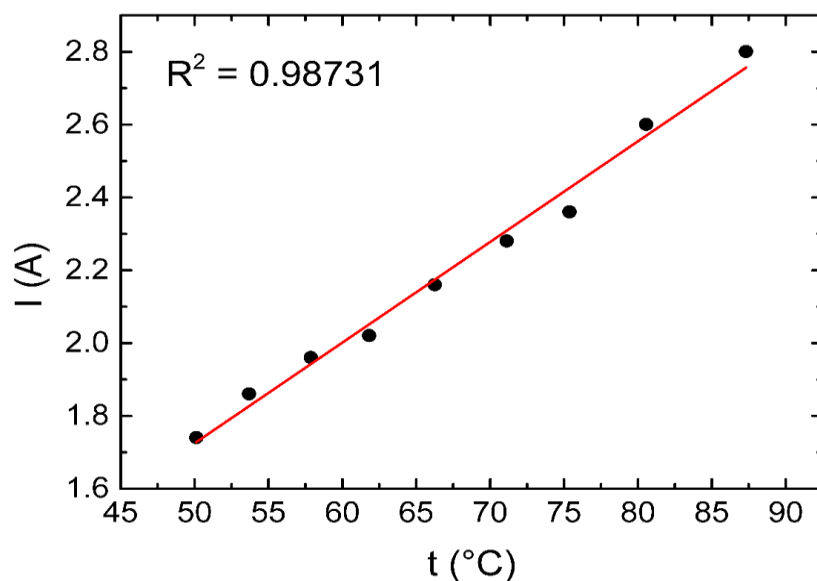


Fig. 5 – The dependence of the current through electrolyte on its temperature. R^2 denotes the coefficient of determination. The full color version may be accessed at <https://rrp.nipne.ro>.

From this graph it follows that the electrical conductivity of the electrolyte depends strongly on the temperature, which is a result of the thermal motion and is consequently related to the mobility of the ions.

4. CONCLUSIONS

We managed to set up a series of digitized didactic experiments through which we studied electrical conduction in liquids. The first two experiments prove that the local form of Ohm's law is also valid for electrolytes. In the last two experiments we demonstrated that this conduction is provided by the ions in the solution and depends on both the number of ions and their mobility. Other experiments related to the conduction of electric current in liquids can be performed, but the ones already performed here are relevant from didactical point of view.

Using devices like the Raspberry Pi does not expensive and helps us to carry out experiments relevant to the teaching process. Also, by displaying it on a large screen (like a smart board) we can make the digital experiments visible to the whole class, which is not always possible in the case of traditional experiments.

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