

# Experimenting from a distance in case of Rutherford scattering

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**Abstract.** The Rutherford scattering experiment plays a central role in working out atomic models in physics and chemistry. Nevertheless, the experiment is rarely performed at school or in introductory physics courses at university. Therefore, we realized this experiment as a Remotely Controlled Laboratory (RCL), i. e. the experiment is set up in reality and can be operated by a computer via the Internet. We present results of measurements and supplementary didactical material. In addition, we make suggestions on how to use the RCL in class and we describe the added value of performing this experiment as an RCL.

## 1. Introduction

The Rutherford scattering experiment ( $\alpha$ -particles scattered by nuclei of a thin metal foil) plays a central role in working out atomic models in physics as well as in chemistry either at school level or at the first year at university. In general, this experiment is used to confirm theoretical predictions from scattering data like angular dependence of scattered  $\alpha$ -particles, dependence on atomic number  $Z$  of scattering nuclei and scattering statistics.

Although the theoretical derivation of Rutherford's scattering formula is based only on the Coulomb interaction between two pointlike charges and laws of mechanics, its treatment exceeds school level. On the other hand, it is used as a standard problem in teaching physics at university. Rutherford's scattering experiment as a demonstration experiment is offered by specific companies (for example, Leybold Didactics, Phywe, Pasco), but the real experiment is rarely performed in class because of several reasons:

- (1) The experiment is not widely available in schools or universities since the technical setup is too expensive (about 1500 €) in relation to a usage of once or twice per year.
- (2) The time required to measure the dependence between scattering angle and scattering rate, in particular for the more relevant larger angles, is too long to be performed in class (much more than 20 minutes) even if the activity of the  $\alpha$ -particle source is already the highest possible to fulfill security standards (340 kBq in case of Am-241, German situation).
- (3) The learners have very few opportunities to participate during the measuring process, since the experimental setup is typical for a demonstration experiment performed by the teacher.
- (4) The measurement is not very exciting, because one has to register only time intervals and the number of  $\alpha$ -particles displayed by a counter.

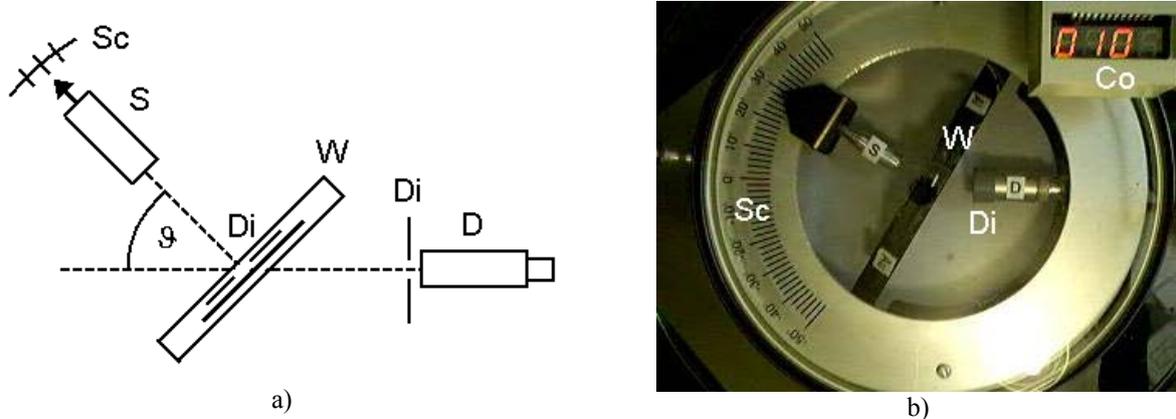
In the following we describe the principle of a Remotely Controlled Laboratory (RCL) and present Rutherford's scattering experiment as an RCL variant. To conclude, we comment on the quality of the measured data, give some hints for teaching and refer to additional didactical material.

## 2. RCL variant and experimental results

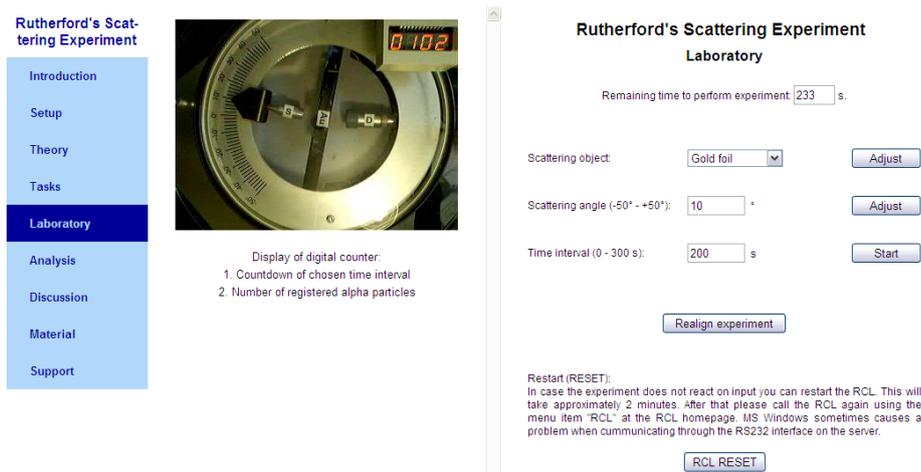
The concept of an experiment as an RCL is that a real experiment located at A can be controlled by a user with a computer located at B via the Internet. The RCL is available 24 hours and 7 days a week. The interested reader will find more general information about technique, programming, didactics, experiences and acceptance in two basic articles [1, 2].

For the present RCL we used and modified the experimental setup supplied by LD Didactic [3]. Figure 1a shows the scattering geometry, figure 1b the view of the web camera on top of the experiment; Am-241 as source of  $\alpha$ -particles, a motorized wheel with gold foil (Au), aluminium foil (Al) and slit (—)

as scattering objects and a semiconductor detector for registration of scattered  $\alpha$ -particles. In order to measure the number  $N_D$  of scattered  $\alpha$ -particles as a function of scattering angle  $\vartheta$  the source together with the scattering object can be rotated with respect to the detector. A counter registers the number of scattered  $\alpha$ -particles in a time interval  $\Delta t$  which can be chosen by the user. The equipment for scattering and detection is mounted inside a vacuum chamber.

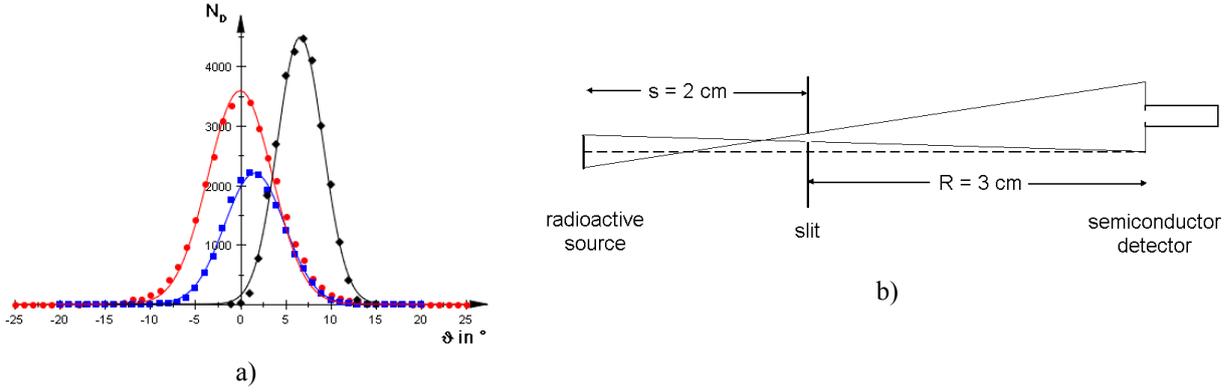


**Figure 1.** a) Scattering geometry, view from top. b) View of the web camera on top of the experiment. Radioactive source (S), wheel (W) with aluminium foil (Al), slit (—) and gold foil (Au), detector (D), diaphragms (Di), display of counter (Co) for number of registered  $\alpha$ -particles and scale (Sc) for reading the scattering angle.



**Figure 2.** From the RCL website, menu item “Laboratory”: menu bar of the RCL (left), view of web camera (middle) and control panel to vary technical parameters (right).

Figure 2 represents the laboratory website: the left part shows the RCL menu which is identical in all our various RCLs. The middle part shows the streaming live image of the web camera. The right part represents the control panel of the laboratory with the controls; one can choose a scattering object (Au, Al, slit) and a scattering angle ( $-50^\circ \leq \vartheta \leq 50^\circ$ ). The execution of the commands can be viewed in the image of the web camera. After selecting a time interval ( $\Delta t \leq 300$  s) and starting the measurement the counter displays a countdown of time in seconds. Then, after finishing the registration, the counter displays the number of detected  $\alpha$ -particles. The button “Realign experiment” sets all movable components in a defined position, the button “RCL RESET” restarts the computer in case of communication problems between interface of the experiment and web server.



**Figure 3.** a) Number  $N_D$  of registered  $\alpha$ -particles as a function of scattering angle  $\vartheta$  for slit (diamonds), gold foil (circles) and aluminium foil (squares). Experimental data can be approximately modelled by a Gaussian distribution (lines). b) Arrangement of source, scattering foils and slit, respectively, and detector. View from top.

Figure 3a shows measurements of the number  $N_D$  of registered  $\alpha$ -particles for three scattering objects (Au, Al, slit); each data point represents acquisition during a time interval  $\Delta t = 300$  s. Interpretation of data delivers the following results.

- The distribution of data in case of aluminium and slit are not symmetrical with respect to  $\vartheta = 0$ , because the source, the scattering objects and the detector cannot be positioned on a straight line without too much technical effort (figure 3b) [4]. In order to get the offset angle  $\vartheta_0$  the experimental data can be described by means of a Gaussian distribution

$$N_D(\vartheta) = N_{max} \cdot e^{-b(\vartheta - \vartheta_0)^2} \quad (1)$$

as a first approximation.

- The distribution of data points in case of the slit is not a rectangular one because the source (active area  $\sim 5$  mm<sup>2</sup>), the irradiated area ( $\sim 4$  mm<sup>2</sup>) and the detector area ( $\sim 3.8$  mm<sup>2</sup>) are not pointlike (figure 3b). Therefore, the measured distributions in case of gold and aluminium foil for small scattering angles are mainly determined by the geometry of the setup and partly by multiple scattering events. (Rutherford's scattering formula is based on single scattering and it diverges for  $\vartheta \rightarrow 0^\circ$ .)
- The integrals of the distribution for the slit and gold foil are nearly equal. Therefore, we can conclude that only a few  $\alpha$ -particles are absorbed in the gold foil. The integral of the distribution in case of aluminium foil is smaller by a factor of about 0.6, since the ratio of thickness of both foils is  $d_{Al}:d_{Au} = 4:1$  and since the energy loss is larger for lower  $Z$  materials.
- The distribution of data points in case of gold and aluminium is broader than the distribution in case of the slit, because  $\alpha$ -particles are scattered in directions of larger scattering angles.

For further analysis of the experimental data we make use of the Rutherford formula for scattering of  $\alpha$ -particles as it is given in standard university text books:

$$N_D(\vartheta) = N \frac{ndA_D}{R^2} \left( \frac{Ze^2}{8\pi\epsilon_0 E_{kin}} \right)^2 \cdot \sin^{-4} \left( \frac{\vartheta}{2} \right) = k \cdot \sin^{-4} \left( \frac{\vartheta}{2} \right). \quad (2)$$

By means of

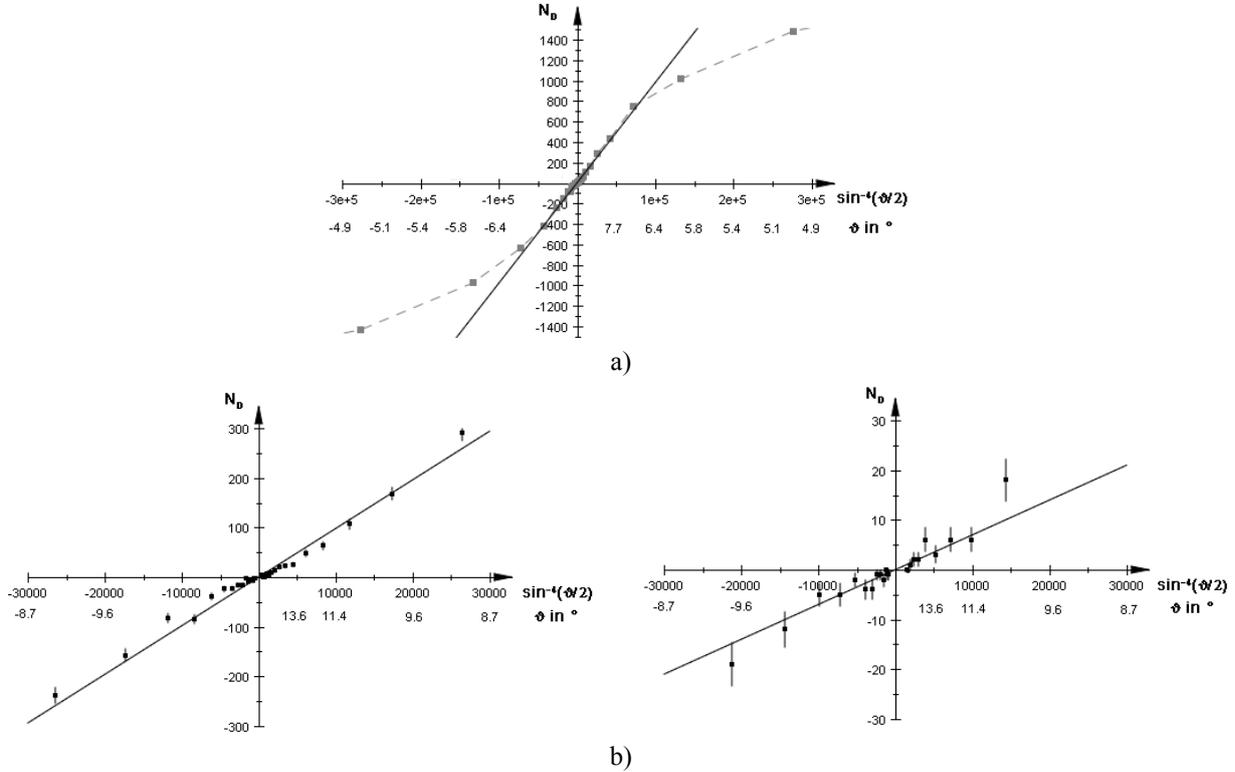
$$Z = \frac{8\pi\epsilon_0 E_{kin}}{e^2} \sqrt{\frac{kR^2}{NdA_D}} \quad (3)$$

the atomic number  $Z$  can be determined and the formula

$$N = A \cdot t \cdot \frac{A_F}{4\pi s^2} \quad (4)$$

can be used to determine the number  $N$  of  $\alpha$ -particles passing the area  $A_F = 4$  mm<sup>2</sup> of slit or metal foil with the activity  $A = 340$  kBq of Am-241 source. The other quantities read as follows: number  $N_D(\vartheta)$  of

registered  $\alpha$ -particles during measuring time  $t$  and in direction of scattering angle  $\vartheta$ , kinetic energy  $E_{kin} \sim 4.5$  MeV of  $\alpha$ -particles [5], element number  $Z$  ( $Z_{Au} = 79$ ,  $Z_{Al} = 13$ ), thickness of foils  $d$  ( $d_{Au} = 2$   $\mu\text{m}$ ,  $d_{Al} = 8$   $\mu\text{m}$ ), distance  $R = 3$  cm between scattering centre and detector, area  $A_D = 3.8$  mm<sup>2</sup> of detector, density of nuclei  $n$  ( $n_{Au} = 5.90 \cdot 10^{28}$  nuclei/m<sup>3</sup>,  $n_{Al} = 6.03 \cdot 10^{28}$  nuclei/m<sup>3</sup>), distance  $s = 2$  cm between source and scattering centre [6].



**Figure 4.** a) Number of registered  $\alpha$ -particles  $N_D$  as a function of  $\sin^4(\vartheta/2)$  for gold foil and scattering angles  $|\vartheta|$  below ca.  $25^\circ$  (grey squares and dashed line). For simplicity the sign of  $N_D$  is inverted for  $\vartheta < 0$ . Theoretically predicted values  $N_D(\vartheta) \sim \sin^4(\vartheta/2)$  for scattering angles  $|\vartheta| > 6^\circ$  (straight line). b) Number of registered  $\alpha$ -particles  $N_D$  as a function of  $\sin^4(\vartheta/2)$  for gold foil (left) and aluminium foil (right) and scattering angles  $8^\circ < |\vartheta| < 25^\circ$  (squares). Results of a linear fit are shown as straight lines. Again, the scale of  $N_D$  is inverted for negative angles.

Figure 4a shows that in case of the gold foil the theoretical formula of Rutherford scattering does not agree with experimental data for scattering angles  $|\vartheta| < 7^\circ$ . To show that in our case there is no influence of the short range nuclear force on Rutherford scattering, we calculate the shortest distance  $r_{min}$  between  $\alpha$ -particles and scattering nuclei, which would appear during central collision, by means of conservation of energy. We then compare this distance with the radius  $r$  of the nuclei. For the relatively small kinetic energy of  $\alpha$ -particles ( $E_{kin} \sim 4.5$  MeV) we get  $r_{min,Au} \sim 51$  fm and  $r_{min,Al} \sim 8$  fm which is at least twice the nuclear radii  $r_{Au} \sim 7.0$  fm and  $r_{Al} \sim 3.6$  fm.

Figure 4b shows that for scattering angles  $|\vartheta| > \text{ca. } 8^\circ$  the scattering distribution of the gold foil and aluminium foil is described by  $N_D(\vartheta) \sim \sin^4(\vartheta/2)$ . Moreover, from the slopes  $k_{Au} = 0.0093$  and  $k_{Al} = 0.00089$  of the regression lines and with the help of formula (3) and (4) we can calculate the atomic numbers  $Z_{Au} \sim 116$  (79 in reality) and  $Z_{Al} \sim 18$  (13). There are at least two reasons to explain the deviations. First, we have to consider that  $Z$  is determined from many parameters ( $d$ ,  $A_D$ ,  $R$ ,  $N$ ) with uncertainties of about 10 % plus statistical error in the  $k$ -value. Second, in addition to the energy loss caused by the coating of the radioactive material [5], an energy loss occurs in the respective metal foils ( $\Delta E_{kin,Au} \sim 0.4$  MeV,  $\Delta E_{kin,Al} \sim 0.5$  MeV). Taking all this into account we can correct the element number from our experiment to be  $Z_{Au} \sim 86$  and  $Z_{Al} \sim 12$  with an error of about  $\pm 10$  %. This result is quite satisfactory with respect to the simple setup.

### 3. Use in class and supplementary materials

Generally, to integrate an RCL in a teaching sequence the teacher may present the principal setup as a demonstration experiment, only short and qualitative. As homework each student or groups of students can measure part of the whole measuring program to collect enough data. The students may communicate over the Internet with suitable communication tools. Data analysis can be prepared before by the teacher in general, so that the students can independently analyse their own data and present them for discussion in class.

To support teachers at school we developed various didactical materials. In the RCL menu one finds all necessary information about the experiment: The menu items “Setup” and “Material” contains all information of a technical kind, such as scattering geometry, electronics, data of components of setup etc. In the menu item “Theory” we put a lot of effort, because we think that the textbook situation – school level as well as university level – is not elaborated enough: either only Rutherford’s scattering formula is given without explanations or the derivation of this formula is mathematically driven. Therefore, we

- explain the measured data of the scattering experiment in different atomic models (Dalton, Thomson, Rutherford), i. e. we compare theoretical expectation and experimental results.
- develop the structure of Rutherford’s scattering formula, that is the dependence of  $N_D$  on distance ( $\propto 1/R^2$ ), on number of  $\alpha$ -particles ( $\propto N$ ), on angle ( $\propto 1/\sin^4 \vartheta$ ), on element number ( $\propto Z^2$ ), on geometry, on kinetic energy of  $\alpha$ -particles ( $\propto 1/E_{\text{kin}}^2$ ).
- compare theoretical predictions on the basis of pointlike charges and coulomb forces with experimental data and we comment on severe deviations.
- offer theoretical background for planning measurements on angular distribution  $N_D(\vartheta)$  and determination of element number  $Z$  of scattering object.
- describe the statistical process and comment on the uncertainties of all measured data.

The menu item “Tasks” offers questions and problems to the measuring program either for quick single measurements or series of measurements. The user can select, plan and perform his or her own way to run this experiment. The menu item “Analysis” presents results of our sample measurement for comparison to own measurements, and, in addition, a prototype data and error analysis. The menu item “Discussion” contains questions about setup, theory, experiment and analysis which should deepen the knowledge of the user. Additionally, in the menu item “Material” the interested reader will find (1) a very comprehensive collection of problems with elaborated solutions: problems about theory, about experimental setup, about measurements and data analysis (16 problems, 57 questions, about 40 pages), (2) experimental data in case of gold foil for large scattering angles  $|\vartheta| < 50^\circ$  (at constant statistical error of  $\sim 15\%$ ) where the time intervals of measurement become very large (up to 22 h) in order to proof the validity of Rutherford’s scattering formula for an extended range of scattering angles, (3) a hyperlink to an elaborated teaching sequence for teachers in German [7].

### 4. Conclusion

Rutherford’s scattering experiment is well suited to be performed as an RCL. The quality of experimental results (scattering distribution, determination of element number, uncertainty of measurement) is high enough to be checked by theoretical predictions. The added value of Rutherford’s scattering experiment as an RCL is as follows.

- The RCL is very flexible and controllable with only a few control elements. It allows single measurements and series of measurements as well as to plan and perform measuring programs according to ones own research interest like going to larger angles or decrease statistical errors.
- Students can measure autonomously, they can collect enough data to formulate statements at a scientific level and they can communicate about their results.
- The RCL fosters and catalyzes new methods of teaching and learning about atomic models.
- Supplementary materials allow teachers to adapt their teaching method to different learners (basic, advanced) and different situations and to concentrate on guiding and moderating the learning process.

In the framework of our project [8] about 20 RCLs have been set up in such a way, e. g. “Photoelectrical Effect”, “Radioactivity”, “Wind Tunnel”. The first experiments went online in 2001. Since then we register about three to five users per day per RCL, on total about 18.000 visitors of our portal per year worldwide from about 40 countries. This fact mirrors a certain acceptance of our approach and, finally, it shows that the experiments are working stably.<sup>1</sup>

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### References

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- [2] Gröber S, Vetter M, Eckert B and Jodl H-J 2008 Remotely controlled laboratories: aims, examples, and experience *Am. J. Phys.* **76** 374-8
- [3] LD Didactic Instruction Sheet “Scattering chamber after Rutherford, gold- and aluminium foil in holder” No. 55956/54/52, <http://www.leybold-didactic.de/ga/5/559/55956/55956E.PDF>.
- [4] The setup is aligned for the position of gold foil (figure 3a).
- [5] Since the decay of Am-241 consists of several  $\alpha$ - $\gamma$  cascades the weighted mean energy of  $\alpha$ -particles is about 5.47 MeV. In addition, when passing the coating of the source the kinetic energy of the  $\alpha$ -particles is reduced to about 4.5 MeV.
- [6] <http://rcl.physik.uni-kl.de>; see “Rutherford’s Scattering Experiment” Section “Theory”
- [7] Gröber S 2008 Entdeckung des Atomkerns – RCL “Rutherford-Streuversuch” <http://www.lehrer-online.de/rutherfordscher-streuversuch.php> (in German)
- [8] Our website is at <http://rcl.physik.uni-kl.de>

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<sup>1</sup> In order to reach German teachers, who are not reading English journals regularly, we published a similar article but with different emphasis about this RCL in the German journal *Praxis der Naturwissenschaften – Physik in der Schule* **58/4** (2009), pp. 41-44.