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Rutherford cross sections measured with nuclear track detectors

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Abstract This paper presents a Rutherford scattering experiment with a 10 μCi ^{241}Am source licensed for schools using commercial foils of dielectrics for α particle detection. In a simple set up the cross sections of Au are measured up to scattering angles of 110°. The Z^2_{target}-dependence of the cross section is verified precisely.

Zusammenfassung Wir zeigen ein Rutherford experiment mit einer für Schulen zugelassenen 10 μCi ^{241}Am Quelle, in dem dielektrische Folien zum Nachweis der Alphateilchen benutzt werden. In einem einfachen Versuchsaufbau wird der Wirkungsquerschnitt von Au bis zu Streuwinkeln von 110° gemessen. Die Z^2_{Target}-Abhängigkeit des Wirkungsquerschnitts wird exakt nachgewiesen.

1. Introduction

In spite of its great importance the Rutherford/Geiger experiment (Rutherford 1911, Geiger and Marsden 1913) in which they discovered the atomic nucleus is not standard in practical physics teaching. However, the experiment is simple using foils of nuclear track detectors, which are sensitive to α particles (Knoll 1979, Fleischer *et al* 1975). If an α particle hits the foil, it loses energy, producing a trail of damaged molecules. The number of traces per unit area caused by registered particles as a function of scattering angle can be counted after etching the foil and enlarging the region of interest. The traces produced are in the order of μm. Kodak offers a suitable detection foil specially designed for α particle registration (LR 115-II): the layer sensitive to the α particles is 13 μm thick and of intense red colour. Etching tracks passing through this 13 μm layer can be seen in an enlarged hard-paper copy as black dots on white background. Alpha-particles of more than approximately 2 MeV energy produce traces longer than 13 μm in this material, but those with a lower energy than this cannot pass through the total thickness before being completely deaccelerated. On the other hand the energy loss of α particles with more than about 4 MeV energy is too small to produce tracks that can be made visible by etching.

The main problem in constructing a Rutherford experiment suitable for educational courses is the extreme low 'beam current' of the licensed low activity sources; high angle scattering is scarce. In this field of low intensity counting, nuclear track detectors dominate electronic detectors for the following reasons:

(i) With nuclear track detectors all scattering events in the region $0° < \theta < 120°$ are detected simultaneously thus saving time;

(ii) The solid angle of the nuclear track detector can be made large for a low price (the experiment described here costs less than 2 DM per run);

(iii) Long measuring times are no longer a problem because no observation is needed during the run. No electronic devices can be destroyed by the students.

(iv) Personal counting in a Rutherford experiment resembles the original work in the laboratories at the beginning of the century.

(v) The paper copy of the irradiated foil makes the total distribution of the scattering events visible.

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Rutherford and Geiger's experiments which lead to the well-known cross section (in SI units)

$$\left(\frac{d\sigma}{d\Omega}\right)_\theta = \left(\frac{1}{4\pi\varepsilon_0}\right)^2 \left(\frac{Z_1 \cdot Z_2 \cdot e^2}{4E}\right)^2 \cdot \frac{1}{\sin^4(\theta/2)}$$

can be subdivided into: measuring the cross section for Z_2 fixed as a function of scattering angle θ (the difference between angles measured in the laboratory and centre-of-mass frames will be disregarded); measuring the cross section for fixed scattering angles as a function of Z_2.

2. The experiment

2.1. Apparatus

Figure 1 shows a schematic drawing of the simple apparatus we used: source, aperture, target, detector foil. For scattering angles higher than 20° the target is tilted to 45° with respect to the direction of the α-particle 'beam'. The beam spot on the target, i.e. the region where scattering takes place, is defined by an aperture of 2 mm or 4 mm diameter. To simplify the set up as much as possible the aperture itself is tilted and the target is mounted directly on the frame the aperture is drilled in. Of course this mounting reduces the effective scattering area by a factor of cos(45°). To reduce α particle scattering along the walls of the defining aperture the material (brass) surrounding the aperture is milled down to 0.2 mm. To vary the solid angle of the aperture with respect to the source, i.e. to vary the 'beam intensity', the source is mounted at a distance of 41 mm or 56 mm respectively. Using a 9 μCi source the 'beam intensity' on the target can be varied within the limits of 16 to 130 particles s^{-1}. (cf the typical current on accelerators is of the order of 100 nA, i.e. 10^{12} particles s^{-1}!) The detector foil is mounted on a cylindrical frame covering the scattering angles −90° to +120° with the beam spot on the target in its centre (r = 20 mm). During an experiment the apparatus is housed in a standard low vacuum recipient.

2.2. Targets

The targets of pure gold, cadmium, copper, and aluminium are mounted on suitable frames. Target thickness was measured with a surface barrier detector by the method of range differences. To measure the angular dependence of the Rutherford cross section the gold target was chosen to be 2.3 μm thick. With the target tilted to 45° and scattering in $\theta = 100°$ the α particles leave the target with 2.3 MeV energy, just above the lower threshold of the detector sensitivity.

The mean weighted scattering energy $E^* = (\langle E^2 \rangle)^{1/2}$ fixing the mean cross section follows from the known energy–range relation of α particles in gold (Northcliff and Schilling 1970). With target thickness D the energy $\langle 1/E^2 \rangle$ is calculated as

$$\left\langle \frac{1}{E^2} \right\rangle = \frac{1}{D} \int_0^D \frac{1}{E^2(x)}\, dx.$$

With $E(0) = 4.2$ MeV, $D = 2.3\ \mu\text{m}/\cos(45°)$ E^* is calculated as 3.36 MeV.

2.3. Alpha-particle source

The experiment is designed to run with a standard

Figure 1 The apparatus showing: 9 μCi ^{241}Am source; The source housing which can be placed 56 mm or 41 mm from the aperture; The defining aperture which is either 4 mm or 2 mm diameter; The target, which can be moved into a position perpendicular to the beam; Mounting with the detector foil inside facing the target—small holes are drilled to mark the positions of $\theta = 0°$, $\theta = 90°$ on the detector foil; flexible pasteboard shielding.

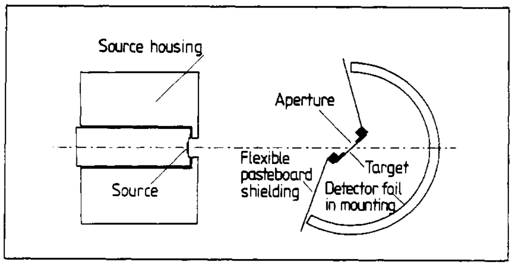
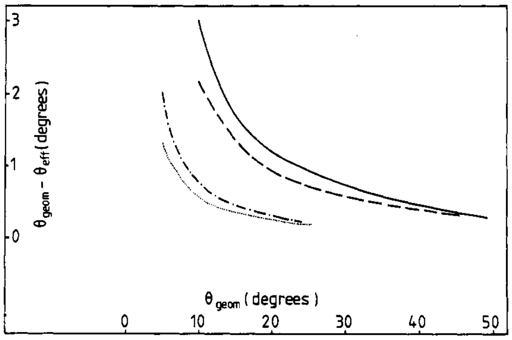


Figure 2 For small scattering angles the geometric scattering angle is higher than the effective scattering angle. The curves are calculated for an aperture tilted at 45°. With an aperture of 4 mm diameter the full (broken) curve shows results for a source-aperture distance of 41 (56) mm respectively. With a 2 mm diameter aperture the results are shown by the chain (dotted) curve respectively.



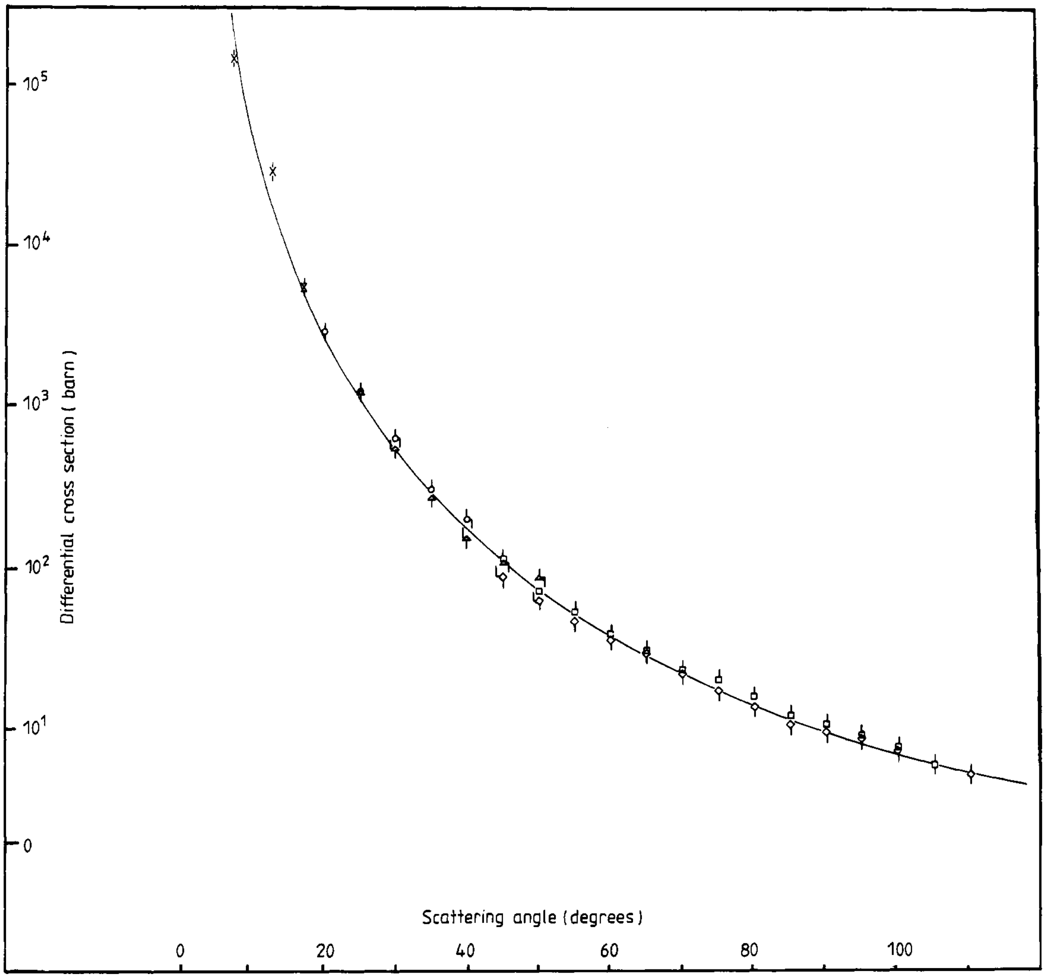


Figure 3 Cross sections of Rutherford scattering of 3.4 MeV α particles on Au measured with nuclear track detectors. The meaning of the symbols is given in table 1. The full curve represents the calculated cross section (not normalised) with the parameters given in section 2.

^{241}Am source of maximum activity licensed for schools in Germany (10 μCi). The activity of the source was measured to be 9 ± 1 μCi. Because of radiation protection this source is covered with a layer of metal 4 μm thick which deaccelerates the 5.5 MeV α particles to 4.2 MeV.

2.4. Determining the scattering angle

The distribution of scattering angles at a given detector position is attributed to two effects:

(i) The beam spot on the target is of finite dimensions.

(ii) The α particle beam reaches the aperture with 4.2° divergence at maximum.

We calculated the resulting angular distribution. Weighting the distribution with $\sin^{-4}(\theta/2)$ gives the effective scattering angle (figure 2).

Only for scattering angles smaller than 20° the effective scattering angle differs slightly from the mean geometric scattering angle. The difference between laboratory and centre-of-mass (cm) angle can be disregarded. (For scattering on Au: $\theta_{\mathrm{Lab}} = 100° \triangleq \theta_{\mathrm{cm}} = 101.3°$.)

2.5. Handling the detector foil

Only because tracks passing the intense red layer of

13 μm thickness are visible in the paper copy of the etched foil, this device is relatively insensible to mechanical damage. All other nuclear track detectors we know are transparent or semitransparent and can be handled only with gloves, because all damage will cause an 'event' on the detector foil. But micro scratches can hardly be distinguished from real events caused by α particles.

The irradiated foil is etched for 90 minutes in 2.5 N solution of NaOH. Enlargement of a linear factor of 15–20 is sufficient to copy the tracks in the foil on paper. For counting the black dots we used a pocket lens and a grating of 0.5 cm or 1 cm width respectively.

The traces of α particles that lose too much energy in the target to pass the 13 μm thick sensitive layer in the detector foil are not copied on paper. But these tracks are visible with a microscope too. So it was simple to check that even at the higher scattering angles correction for loss of tracks was not necessary.

3. Results

3.1. *The cross section on gold*

Figure 3 gives the cross section measured on gold for scattering angles ranging from $\theta = 7°$ up to $\theta = 110°$. The cross section varies for five decades of magnitude. The data are collected in five independent runs giving very consistent results.

Measurements up to 50° can be taken with reasonable statistical accuracy in one day, data collection up to 110° needs five days of irradiation. For the scattering leading below 20° the data points are graphed at the effective scattering angle according to figure 2 ($9.2° \rightarrow 6.9°$, $13.8° \rightarrow 12.5°$, $18.3° \rightarrow 17.4°$) The error bars are of the order of ±15% as calculated from the source calibration (±11%) and the counting statistic (±7%). The data are compared with the absolutely calculated cross section.

3.2. *The Z_2^2 dependence of the cross section*

To investigate the Z_2^2 dependence of the Rutherford cross section target elements with $Z_2 = 13$, 29, 48, 79 were used covering a wide range of the periodic system. Data collection runs for one day at a fixed scattering angle of 20°. In all target foils the α particles suffered approximately the same energy loss. Therefore the mean scattering energy stayed unchanged.

Figure 4 gives the number of registered α particle tracks at $\theta = 20°$ corrected for different numbers of scattering centres per unit area in the different targets.

Following the Rutherford cross section formula the definition of the cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_\theta = \frac{N(\theta)}{\Delta\Omega_{\mathrm{Det}}((L/A)\rho d)tn}$$

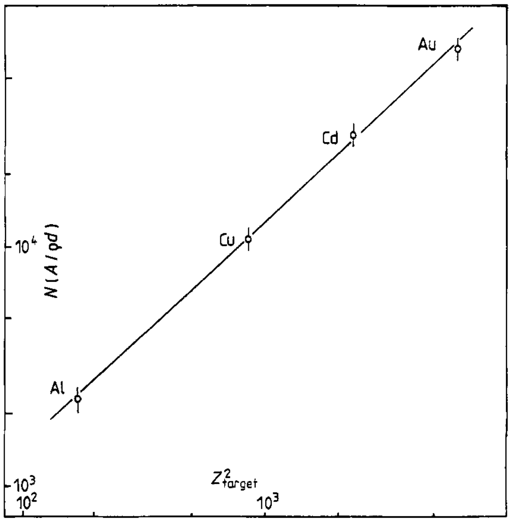
leads to

Table 1 Details of the five experiments presented in figure 3: ϕ angle defined by beam direction and target normal; d source–aperture distance; t measuring time; θ smallest/highest scattering angle; N number of tracks per mm^2 registered in the detector foil during time t at θ.

Symbols	Aperture diameter (mm)	ϕ	d (mm)	t (h)	$\theta_{\min}$ (N)	$\theta_{\max}$ (N)
Cross†	1.5	0°	45	2.3	7° (400)	—
				4.6	12° (152)	17° (29)
Circle	2	0°	41	23	20° (310)	45° (13)
Triangle	2	45°	41	23	25° (162)	60° (5.3)
Rhombus	4	45°	41	120	45° (245)	110° (15)
Square	4	45°	56	220	45° (322)	105° (17)

† These data are measured with a preliminary apparatus.

Figure 4 Z_{target}^2 dependence of the Rutherford cross section. The factor $A/\rho d$ corrects for the different numbers of scattering centres per unit area. The line is fitted to the data.



$$Z_2^2 \sim \frac{N(\theta)}{(L/A)\rho d}$$

where $\Delta\Omega$ is the detector solid angle, L is Avogadro's number, A is the atomic weight of the target element, d the thickness of the target, t the measuring time, n the number of incident particles per unit time.

The data in figure 4 can be fitted quite well with a straight line as it is expected from Rutherford's theory.

4. Discussion

The Kodak foil (LR 115-II) is shown to be an ideal detector for Rutherford experiments in educational courses. The handling of this detector is non-trivial but delivers results that cannot be achieved with any other detector if only 10 μCi activity is available.

The quality of the data depends on the following details.

(i) The accuracy of the mechanical set up. For the chosen distance between target and detector, 20 mm, a scattering angle of 1 degree covers 0.35 mm on the detector foil. Therefore the mechanical set up of defining aperture and detector housing has to be adjusted to within 0.1 mm.

(ii) The detector quality. Because of the low track density at high scattering angles the detector foil must be free of artificial micro scratches. We tested the Kodak LR 115-II, Kodak CN-85, and an overhead projector foil. Only the LR 115-II foil was found to be suitable for students work.

(iii) Varying the aperture. Because of the shape of the $\sin^{-4}(\theta/2)$ function high scattering angles need high 'beam currents' realised with a wide aperture. On the other hand low scattering angles need a small aperture to keep corrections small.

(iv) The accuracy to which the effective scattering angle is known. According to figure 2 the effective scattering angle and the geometric scattering angle are nearly identical for $\theta > 20°$. Measurements below 20° are difficult.

(v) The target position. If data collection should be expanded to $\theta \geqslant 90°$ the target must be tilted with respect to the α particle beam. If the path of an α particle inside the target foil is too long it loses too much energy to be registered in the detector foil ($E_{\mathrm{min}} \sim 2$ MeV).

A scattering angle of 90° in a target tilted to 45° causes the same energy loss as a scattering angle of 45° in a non-tilted target. Therefore, in our experiment we did not have to correct for loss of tracks.

The different attempts to measure Rutherford cross sections with surface barrier detectors (Eaton *et al* 1973, Ramage *et al* 1975, Fichtner 1982, May 1983) illustrate that this is a laborious experiment that gives results no better than presented in this paper. This type of experiment should be done if the use of surface barrier detectors is the main topic for the students. The proof of the atomic nucleus should be done with nuclear track detectors.

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References

Eaton T W and Cheetham D 1973 *Phys. Educ.* **8** 97–101
Fichtner R 1982 *Phys. und Didaktik* **2** 116
Fleischer R L, Price P B, and Walker R M 1975 *Nuclear Tracks in Solids* (Berkeley: University of California Press)
Geiger H and Marsden E 1913 *Phil. Mag.* **25** 604–23
Knoll G F 1979 *Radiation Detection and Measurement* (New York: J Wiley) pp 759–65
May A 1983 *Praxis d. Naturw. Phys.* **32** 83
Northcliff L C and Schilling R F 1970 *Range and Stopping-power Tables for Heavy Ions, Nucl. Data Tab.* **A7** pp. 233–463 (New York: Academic)
Ramage J C, McKeown J, and Ledingham K W D 1975 *Am. J. Phys.* **43** 51–8
Rutherford E 1911 *Phil. Mag.* **21** 669–88