The Rutherford Scattering Experiment

Tony Tyson

April 22, 2013

1 Introduction

The foundations of modern ideas about atomic structure are considered to have been laid by Sir Ernest Rutherford in 1911, with his postulates concerning the scattering of alpha particles by atoms. Two of his students, Hans Geiger and Ernest Marsden (an undergraduate), set out to measure the number of alpha particles scattered out of a collimated beam upon hitting a thin metal foil. They determined the angular distribution of the scattered particles for several different materials, thicknesses and alpha energies. To their initial surprise, Geiger and Marsden found that some alpha particles were scattered through large angles in atomic collisions. This large angle scattering of alpha particles could not be explained by existing theories. This data lead Rutherford to speculate on the structure of the atom and devise a new "nuclear atom" model. His predictions concerning the characteristics of this nuclear atom were confirmed by the subsequent experiments of Geiger and Marsden with the scattering of alpha particles by thin gold and silver foils (Phil. Mag. 25. 605 (1913), Figure 1). Performance of similar experiments in an undergraduate laboratory is not only of historical interest, but serves to demonstrate how scattering experiments provide the physicist with a powerful investigative technique.

The essential idea of Rutherford's theory is to consider the α-particle as a charged mass traveling according to the classical equations of motion in the Coulomb field of a nucleus. The dimensions of both the α-particle and nucleus are assumed to be small compared to atomic dimensions (10^{-5} of the atomic diameter). The nucleus was assumed to contain most of the atomic mass and a charge Ze. On this picture the Z electrons which make an atom neutral would not contribute much to the deflection of an impinging α-particle because of their small mass. Other models had been proposed for atoms at this time ($\sim$1911) to account for features such as optical spectra. One of these (Thomson's Model) pictured the atom as a continuous distribution of positive charge and mass with the electrons embedded throughout. This model predicts a very small amount of scattering at large angles compared to the Rutherford theory since the α-particles traversing this atom rarely see much charge concentrated in a large mass. A derivation of the predictions of the Rutherford theory as well as discussions of other atomic models may be found in the references listed at the end of this guide, which should be read before starting the experiment.

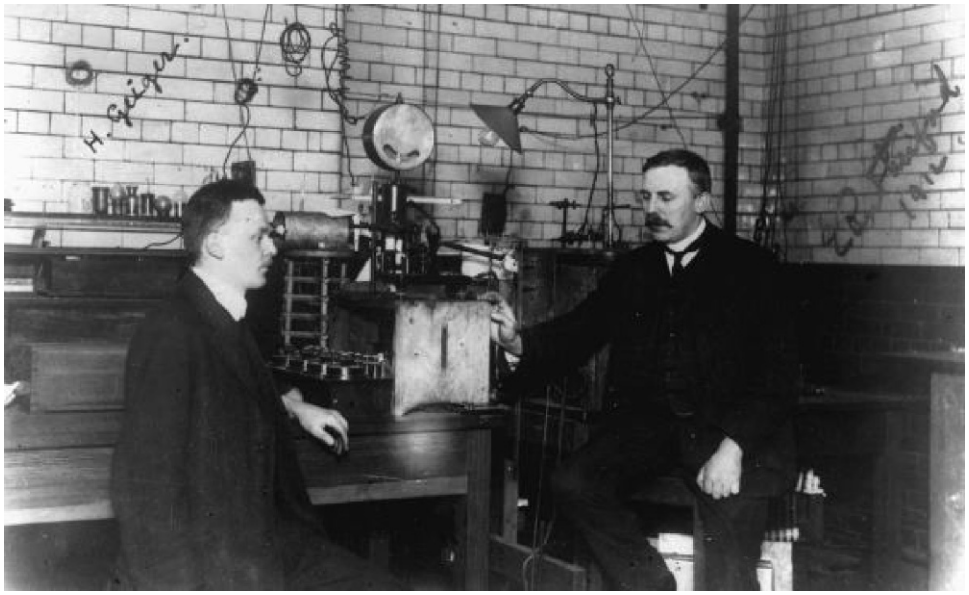

Figure 1: Geiger and Rutherford with their apparatus in 1912. Note autographs. For this setup, Geiger himself was part of the detector: he visually counted flashes of light in the scintillator.

2 Description of Experimental Apparatus

Figure 2 is a simplified cross section of the scattering geometry located in the vacuum system. The α-particle source is a circular foil of 5mm diameter plated with ^{241}Am, and the detector is a 9mm diameter circle of ZnS powder located on the face of a 8575 photomultiplier. The scattering foil is an annulus located coaxially with the α-source and detector with inner and outer diameters, 46.0 and 56.7 mm respectively. The angle β is determined by a fixed distance from source to scattering foil. The scattering angle θ is varied by changing the distance from the scattering plane to the plane of the detector. The metal stop prevents the direct beam of α-particles from striking the detector; however, it can be removed to perform intensity and range measurements.

Figures 3 and 4 show the cage prepared for calibration and for a data run.

A scintillation counter is used to detect the α-particle. In this type of counter the detecting area is covered with a thin coating of zinc sulfide activated by silver doping. When an α-particle strikes a crystal of zinc sulfide, it emits a flash of light. The number of light quanta emitted is approximately proportional to the energy lost by the α-particles in the crystal. If the initial energies of all the α-particle were the same, the number of light quanta emitted for each incident α-particle would be nearly constant. However, small variations in the kinetic energy of the α-particles, variations in the efficiency with which the emitted light is converted into electrical signals and variations in the energy of the α-particles lost in the ZnS crystals give rise to a fairly broad distribution in the size of the pulses from the detector.

The blue light quanta emitted from the ZnS impinge upon the cathode of the photomultiplier and electrons are emitted (the photoelectric effect). The number of electrons emitted by this process is not sufficient for direct electronic detection so that they are first put through an electron multiplier

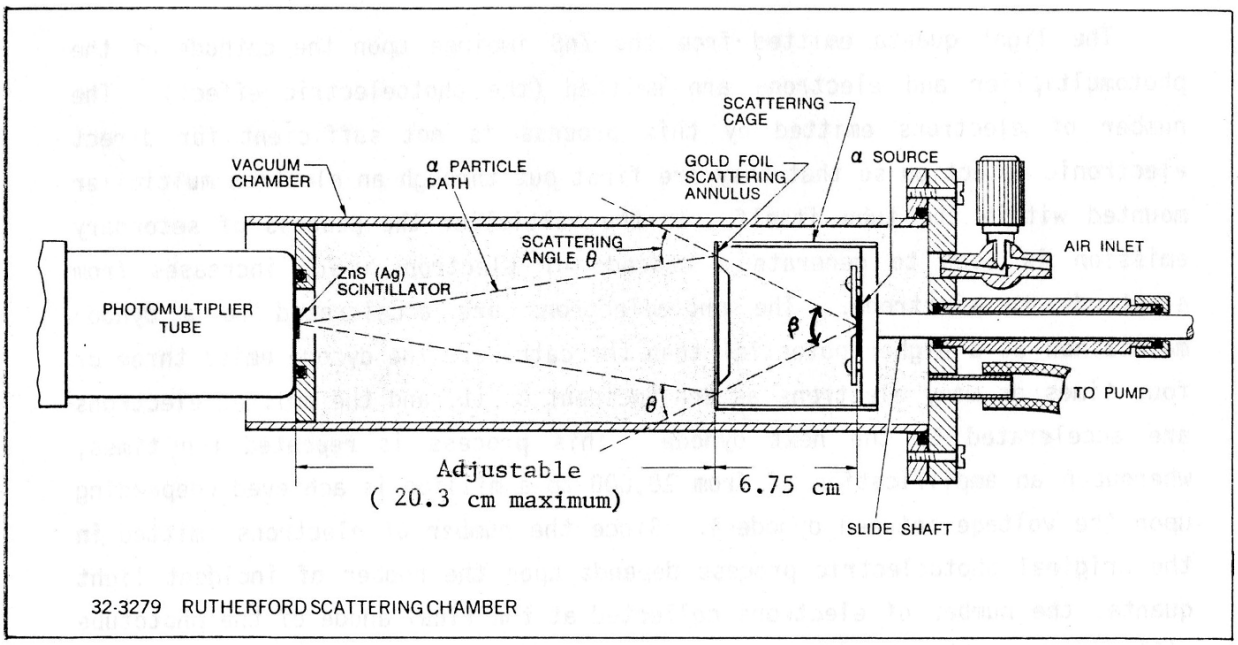

Figure 2: The apparatus. Note the four o-ring vacuum seals. The cylindrical scattering cage can move over a range of about 20 cm from the detector by pushing the shaft (there are stops on the end of the shaft which prevent hitting the detector even with the central plug inserted in the hole in the middle of the scattering foil.) There is a brass shield and plug assembly which can be inserted in front of the scattering foil for calibration. This entire assembly mounts vertically.

Figure 3: This image shows the cage with alpha source and gold scattering foil. Here the brass shield and plug assembly (including washer for spacing away from the gold foil) has been inserted in front of the scattering foil for calibration. The plug has a hole in the middle to form a direct alpha beam, and this can be covered with gold foil to fully simulate the energy loss in the gold foil scattering experiment.

Figure 4: This image shows the cage with alpha source and gold scattering foil prepared for a scattering run. Here only a central plug (without hole) has been inserted.

mounted within the tube itself. In the multiplier the process of secondary emission is used to generate a cascade of electrons which increases from electrode to electrode. The photoelectrons are accelerated to a dynode maintained at a higher potential than the cathode. The dynode emits three or four times as many electrons as are incident on it, and the emitted electrons are accelerated to the next dynode. This process is repeated 12 times, whereupon an amplification of from 10,000 to ten million is achieved (depending upon the voltage between dynodes). Since the number of electrons emitted in the original photoelectric process depends upon the number of incident light quanta, the number of electrons collected at the final anode of the phototube will be proportional to the amount of scintillation light collected. The scintillation light is emitted by the zinc sulfide crystal in about 10^{-4} seconds. The transit time of an electron cascade through the multiplier is less than 10^{-7} seconds. A pulse of current may therefore be observed at the output of the phototube for each α-particle incident upon the zinc sulfide, although the α-particles may arrive in rapid succession. This pulse has a fast leading edge, and then a long trail lasting many microseconds. Thus, you want to filter the pulse and count it within about 1 microsecond, avoiding pulse pileup.

The pulse of current from the photomultiplier charges a capacitor at the input to the preamplifier. The amplifier further increases the size of the pulse and modifies its shape, so that it may be detected and counted by the counter. The proper settings of the amplifier and of the high voltage meter for the phototube will be given in the laboratory. They must be chosen so as to give adequate amplification, but not so much that the pulses are too large for the amplifier to handle properly. As mentioned above, the trapezoidal pulse out of the PMT must be smoothed and then differentiated, yielding a more Gaussian shape of width about 1 microsecond. A pulse forming amplifier is available for that purpose. By adjusting PMT HV and amplifier gains, make sure most pulses are less than 5V peak, and thus unsaturated.

In any electronic circuit electrical ”noise” (unwanted signals) is always present due to the random motions of the electrons in the circuit. In this particular circuit a more important source of noise is

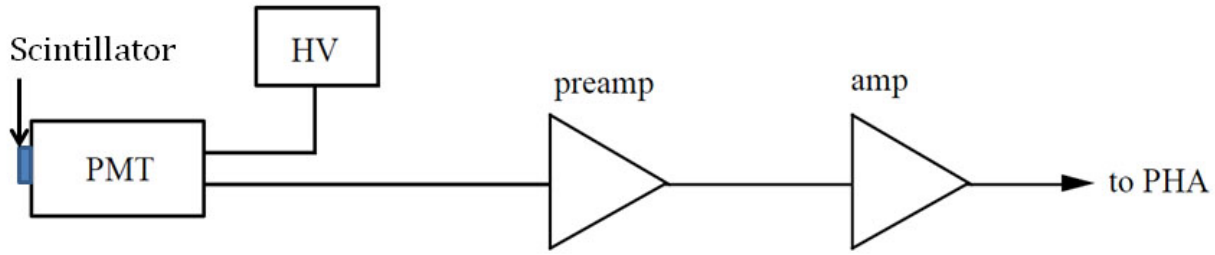

Figure 5: Block diagram of the detector and initial electronics chain. In this experiment you have available two types of pulse-height analyzers (PHA): a multi-channel analyzer (MCA) which can display the full spectrum, and a 2-threshold single channel analyzer (SCA) and counter.

the thermionic emission of electrons from the photocathode which gives rise to signals at the anode that look like small scintillation pulses. A discriminator is used at the input to the counter (as well as the input to the MCA) to prevent these unwanted signals from being counted. The variable potentiometer on the discriminator controls this minimum voltage. In addition, and completely separately from the MCA, you must choose a range of pulse heights (alpha energies) to integrate over, and then count. This is done with the SCA which has upper, lower, and window mode discriminators with a range of 0-10V. Its output can be sent to the counter. After some calibration, you can easily know where to set the SCA window by referring to the MCA spectrum displayed on the XY scope. The block diagram of the front end of the system (up to the pulse height analysis) is shown in Figure 5.

If the pulses were all approximately of the same amplitude, the counting rate would be constant over a range of discriminator settings. When the discriminator lower threshold is set too low the counting rate will increase rapidly because of the PMT noise. If the discriminator is set too high, most of the desired pulses will not be counted. In practice, the desired pulses have a range of sizes so that no narrow peak can be found. However, a range of settings can be found where the counting rate changes only slowly with discriminator setting, and the proper position for the discriminator upper limit during the experiment is at the high counting rate end of the broad peak, (see Figure 6).

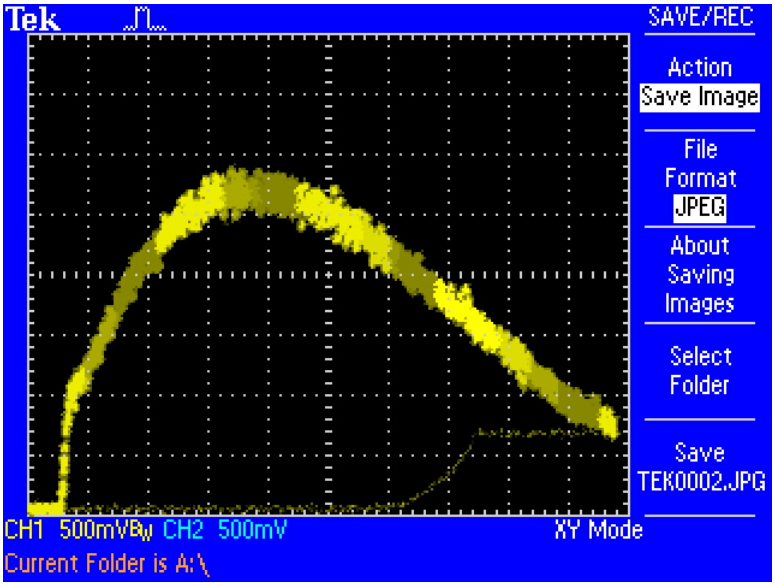

Figure 6: Here the alpha beam was sent direct to the scintillator through a central hole in the plug covered with gold foil. The output of the MCA shows the full spectrum of pulse heights, 0-5V (and thus the spectrum vs alpha particle energy). Little of the PMT noise is seen (note the discriminator on the MCA was set to reject pulses less than about 300mV), and in the middle is the spectrum due to detected alphas. There is a broad peak, and the integral counts over a 1-4.5V window, covering most of this alpha peak, should be obtained for each scattering angle.

Care must be taken not to set the lower discriminator threshold too low, since the background from the PMT can easily overwhelm the signal. Chose a level where the signal/background ratio is around 2 with the source maximally separated from the scintillator. With this setting almost all of the desired pulses will be counted. The background spectrum can be taken with air in the system and the source far away from the detector. At 1800V the PMT noise pulses are usually less than 0.5V out of the preamp (200pF setting). Figure 7 shows the signal spectrum with the source pulled far from the detector.

3 Precautions

1. Always turn off the high voltage before releasing vacuum and exposing the photomultiplier to room light. Exposure to even low levels of room light will *destroy* these photomultipliers which are very expensive.
2. Do not open the vacuum system to air without consulting your instructor.
3. Treat the scattering foil and mounting with care to avoid breaking the delicate foil.
4. Do not touch the ^{241}Am source with anything.

Come to the laboratory with a brief outline of the experiment you intend to perform. You may assume that the following quantities are known:

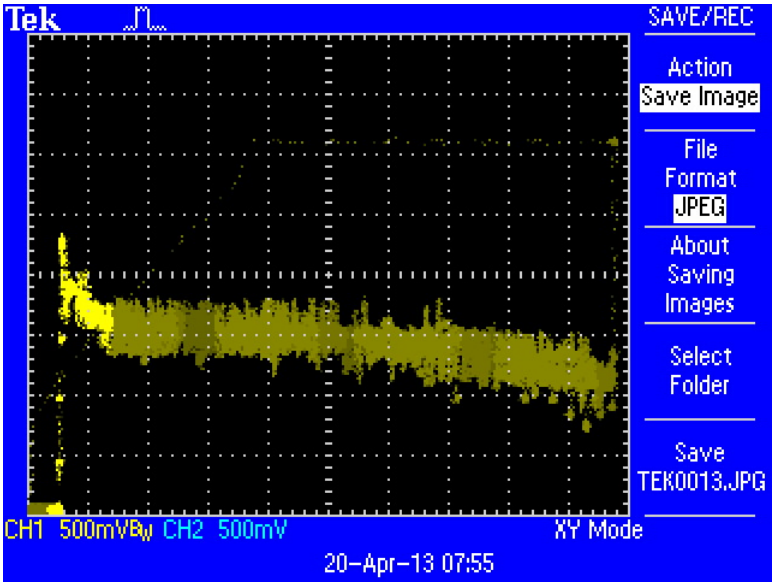

Figure 7: The signal + background is shown using log scale on MCA for the source at its maximum distance from the detector. The output of the MCA shows the full spectrum of the alpha signal at this distance. To set up your filter amplifier window and counter, the dilemma is where to put the lower window threshold: avoiding background by too high a threshold misses much of the alpha signal; too low, and you are swamped by background. In this run, the PMT noise background can be seen as the highlighted upturn at less than 0.7V. The count rate for a 1-4 volt interval was 0.1 counts per second.

- $\frac{1}{2}mv^2$ = 4.7 MeV = the energy of the α-particle (after traversing source window).
- $Ze = 79e$ = total nuclear charge of each scattering atom
- $ze = -2e$ = the charge of the α-particle

The thickness of a single foil is approximately 1 micron or 10^{-6} meter. You will use two layers.

The 5mm diameter ^{241}Am source is covered with a thin 1 micron gold-palladium foil to prevent escape of radioactive daughter products and fragments of the source itself due to embrittlement. The foil on the source reduces the α-particle energy from 5.48 MeV to the 4.7 MeV listed above. α-particles traversing the gold foil in your scattering experiment will lose an additional 1 MeV. There is some additional loss in the ZnS. These losses and other detector inefficiencies give rise to a tail to lower energies seen in the MCA spectrum.

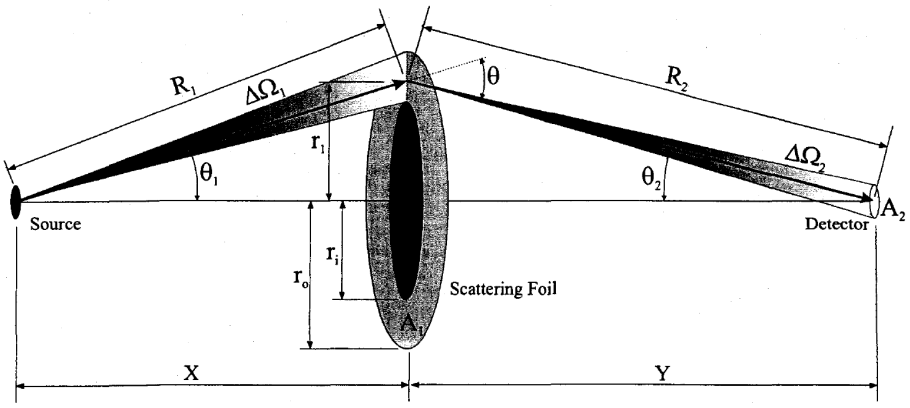

Figure 1: Experimental Geometry

Figure 8: The scattering geometry in this experiment, and definition of parameters. For your setup, X is fixed. You will have to calculate Y from measurements of the extension of the rod. You should make accurate measurements of the geometry of your system.

4 Supplementary Notes

Relation between the differential cross section and the expected counting rate

Definition of differential scattering cross section:

$$\sigma(\theta)d\Omega = \frac{\text{\# of particles scattered at angle } \theta \text{ in a solid angle } d\Omega \text{ per unit time}}{\text{\# of particles incident per unit area per unit time (incident flux)}}$$

Note that the dimension of $\sigma(\theta)d\Omega$ is *area*. From the literature

$$\sigma(\theta) = \frac{Z^2 z^2 e^4}{16E^2} \csc^4\left(\frac{\theta}{2}\right)$$

where:
Ze = the charge of the scattering center,
ze = the charge of the incident particle
E = the kinetic energy of the incident particle
and θ = the angle between the incident and scattered beams.
The coefficient of $\csc^4(\theta/2)$ should be calculated before the experiment.

5 Geometry (Chadwick geometry)

As shown in Figure 2, the scattering angle in this experiment is adjustable by moving the source-foil assembly closer to the detector. Some definitions:

$\Delta\Omega_1$ is the average solid angle subtended by the gold annulus at the source.

$\Delta\Omega_2$ is the average solid angle subtended by the detector at the scatterer.

($\Delta\Omega_2 = d\Omega$ above in the definition of $\sigma(\theta)$.) Approximately :

$$\begin{aligned} \Delta\Omega_1 &\approx \frac{A_1 \cos\theta_1}{R_1^2} \\ \Delta\Omega_2 &\approx \frac{A_2 \cos\theta_2}{R_2^2} \end{aligned}$$

(Check to see how good this approximation is for various angles.)

With the following definitions:

N_0 = the total number of particles emitted by the source per unit solid angle per unit time
A_2 = the area of the detector
A_1 = the area of the scattering material (gold foil)
ρ = the density of the scattering material
t = the thickness of the scattering material
L = Avogadro's number
A_G = the atomic weight of scattering material
$n = \rho L A_1 t / A_G$ = the total number of scattering centers
N_1 = the total number of particles reaching A_1 per unit time $= N_0 \Delta\Omega_1$.

The incident flux is given by

$$\frac{N_1}{A_1 \cos\theta_1} = \frac{N_0 \Delta\Omega_1}{A_1 \cos\theta_1} \sim \frac{N_0}{R_1^2}$$

$N_2 =$ total number of particles reaching A_2 ; per unit time (expected rate):

$$N_2 = (incident flux) \times \quad \sigma(\theta)\Delta\Omega_2 = \frac{nN_0}{R_1}\sigma(\theta)\Delta\Omega_2 = \frac{nN_0 A_2 \cos\theta_2}{R_1^2 R_2^2}\sigma(\theta)$$

$$\theta_2 = \theta - \theta_1, \;\; \theta = \theta_2 + \theta_1$$

$$\mathrm{R}_2 = \frac{\mathrm{r}_0}{\sin\theta_2}$$

$$\text{Expected rate} = \frac{\mathrm{nN_0 A_2} \cos\theta_2 \sin^2\theta_2}{\mathrm{R_1^2 r_0^2}}\sigma(\theta) = \mathrm{N}_2$$

The easiest parameter to measure for different values of the angle θ is the perpendicular distance between the gold annulus and the detector. Let it be y.

$$y = R_2 \cos\theta_2 = r_0 \cot\theta_2$$

$$\begin{aligned} N_2 &= \left[\frac{nN_0A_2}{R_1^2 r_0^2}\frac{Z^2z^2e^4}{16E^2}\right]\left[\frac{\cot\theta_2 \sin^3\theta_2}{\sin^4(\theta/2)}\right] \\ &= N_0 G \qquad f(y) \end{aligned}$$

6 Exercises and Preparation

1. Using the values of the parameters given in the notes, estimate G, assuming $t = 2x10^{-4}$ cm (thickness of 2 gold foils); ρ = 19.32 g/cm^3; fixed distance in Figure 1 = 6.75 cm; $E_{\text{avg}} = 2.5$ MeV (why so low?).
2. $f(y)$ should be plotted versus y before the experiment.
3. Having found G, estimate what N_0 should be for this experiment to give minimum precision (2%) in a reasonable length of time. Remember you will need several points to establish the angular distribution. The curve $f(y)$ vs. y will give you an idea of how to space your points.
4. Why is this geometry advantageous even though it introduces extra angular dependence into the expected rate?
5. Think about how you are going to measureN_0. You are provided with a brass shield that blocks α-particles scattered from the gold. There is a hole in the center of this shield, 2.3 mm (check this) in diameter, which allows an unscattered beam to impinge on the detector.
6. What are the possible sources of *systematic* error?

7 Procedure

1. First you must get detected pulses and then adjust the timing circuitry to give a clean unipolar pulse of 1 microsec time constant approximately. Start with an intense beam of alphas using a plug with an approx 1mm hole (no foil). After adjusting the HV, follow the pulse through the system using the oscilloscope. There will be two amplitude families of pulses: low level background and the higher level alphas. Make sure the alpha pulses are not saturated and are the correct amplitude for insertion into the filter amplifier and the MCA. Repeat this for 2 layers of gold foil covering the hole (why?). Check the pulses out of the filter amplifier and the MCA. Aim for 0-5V.
2. You should have a scattering run generating a pulse height distribution (MCA output). A plateau should be present (see Figure 7). It is suggested that the metal plug with a hole covered with gold foil be first used to view the alpha energy distribution. The height of the voltage pulse is a function of the energy and the lower voltage threshold of the filter amplifier should be adjusted so as to count those α-particles which have lost considerable energy by traversing the gold foil and still discriminate against noise.

3. You must determine the relationship between the measured rod extension and the internal foil-detector distance y. You can make measurements when the system is apart. Be careful not to touch the PMT face or detector with a ruler, and do not shine light on the PMT even when it is off (scintillation lasts for days). Instead, for that measurement use our value of the distance between the bottom of the vacuum flange (system open) and the bottom of the flange at the PMT: 27.7 cm. See apparatus drawing (Fig 3 of apparatus.pdf). To this you should add 1.5mm for the distance from the bottom of the PMT flange to the detector.

4. The dependence of the differential cross section on θ (the scattering angle) can now be found by adjusting the relative position of the scattering foil with respect to the detector. You should plot the expected shape of the intensity vs. y (the perpendicular distance from the scintillator to the plane of the gold foil) assuming Rutherford scattering to be valid. It is suggested that in the laboratory you select $\sim 6-8$ positions covering the entire range of y. For best results, you should integrate over 1000 counts ($\sim$3% statistics) in your optimal pulse height window for each position of the foil relative to the detector. You will find it necessary to carefully plan your runs to take advantage of the lab time and access. If time permits, irregularities in the plot of intensity vs. y can be investigated. Note that at low y scattering angles over 90 deg can be obtained.

5. The strength of the source should be determined, using the brass blocking plate together with the center plug with small hole. A gold foil covering this hole would assure the same energy loss as in the main experiment.

6. Backgrounds must be measured and subtracted from the data before analysis. Plan how you will measure the various backgrounds (PMT, alphas scattering off the inner metal walls ...). Recall that alphas have a short range in air. There is a plastic sheet liner in the tube, so that alphas scatter of it rather than brass (why is this a good idea?).

8 Precautions and Directions on Rutherford Scattering

1. *PMT high voltage OFF when opening phototube to light.*(Also keep fluorescent light away from phototube). You may wish to turn the room fluorescent lights off while the can is out and the tube is open. Use only incandescent lights.

2. Do not exceed 1900V. Raise HV slowly from zero. PMTs are noisy for hours after being turned on.

3. Keep fingers off ^{241}Am source.

4. Treat gold foil with care:

   - Put plug in from top of can.
   - Caution inserting the can into the tube and its plastic sheet sleeve. Move the plastic sleeve down so you can see it and carefully insert the can in the plastic.
   - With can pushed up next to the detector (far away from the air rushing in) let air in slowly (and then turn off pump). Observe this procedure when pumping down, too.

5. *Don't touch* face of phototube with *anything*.

- Keep rulers, etc., away from the tube.
- Make sure plug will not hit the tube.

6. Keep away from the following hot spots.
   - H.V. Supply
   - Internal part of phototube box

9 Tests for Proper Operation

1. Make sure pulse never saturates anywhere in the analog signal chain.
2. Letting air in (slowly) should stop counts.
3. Raising H.V. a little should *not* increase nor decrease counting rate.
4. Raising window upper threshold should not decrease counting rate.
5. Decreasing PMT H.V. slowly to zero volts should stop counting rate.

There are other reactions taking place, that we ignore: Cherenkov radiation, bremsstrahlung and inelastic nuclear interactions. See J.R. Comfort, et al., "Energy Loss and Straggling of Particles in Metal Foils," Phys. Rev. 150, 249 (1966). This article includes data for gold foils.

Equipment supplied

- Vacuum pump
- Rutherford scattering assembly
- Am-241 100 micro Curie alpha source
- ZnS(Ag) scintillator alpha detector
- Burle 8575 12-stage PMT and negative HV base assembly
- Ortec 456 HV supply (operate around 1800V)
- Ortec 113 preamplifier (200pF gain setting)
- Ortek 474 filter amplifier. Start at gain = 20, integ=500ns, diff=200ns, inverted mode.
- LeCroy 3001 MCA V input mode, internal trigger
- Tektronix TDS 2022B X-Y scope for MCA pulse height spectrum display
- Ortec 550 SCA dual adjustable threshold amplifier
- Ortec 772 counter
- Tektronix DPO 3054 scope for pulse shape and timing tests

10 References

1. Melissinos, Experiments in Modem Physics, 1966 edition, see PHY 122 web site.
2. J. Earl, Modified Version of the MIT Rutherford Apparatus for Use in Advanced Undergraduate Laboratories, Amer. J. Physics 34, 483 (1966).
3. R. D. Evans, The Atomic Nucleus, McGraw Hill (1972).
4. E. Rutherford, The Scattering of α and β-Particles by Matter and the Structure of the Atom, Phil. Mag. 21, 669 (1911).