Deflection of Ag-Atoms in a Magnetic Field

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Abstract An apparatus that generates and deflect silver-109 atoms with an inhomogeneous and homogeneous magnetic field was constructed. The experimental results found using this apparatus were used to make a recommendation, to the idea of removing silver-110 atoms from the helium fluid of Pebble Bed Modular Reactor (PBMR) with an inhomogeneous magnetic field based on the Stern-Gerlach principle. It is shown that experimental results corresponded well with the theoretical predictions. The apparatus was also used for a practical for a course for mechanical engineers in modern physics.

Keywords: Ag-atoms, Magnetic circuit, Stern-Gerlach experiment

Nomenclature

B	Magnetic flux density, T
F	Deflecting force, N
m	Mass, kg
v	Velocity, m/s
Z	Distance, m
l	Length, m
μ	Magnetic dipole moment, A.m^2

Subscript

z	z direction in the xyz plane
g	Gap
mc	between a magnet and a second collimator
cc	between two collimators
co	between a crucible and a first collimator

Introduction

A Pebble Bed Modular Reactor (PBMR) was proposed in South Africa in order to create a means of expanding the use of nuclear energy into a variety of industrial and transport sectors (in addition to electricity generation), by supplying clean process heat to produce chemical products, liquid petroleum fuels and hydrogen [3]. The key design characteristic of PBMR is the use of helium coolant and fuel spheres (or pebbles) each containing 15000 triso coated 0.9 particles that produce the nuclear reaction [4]. The fuel spheres can be manufactured economically in large volumes, while maintaining fuel quality and integrity during manufacture and subsequent irradiation [5]. Even under the best manufacturing conditions a small fraction of coated fuel particles will be defective. As a result a fission product ^{110}Ag may be released from the fuel spheres into the coolant gas and may then plate out on the cooler surfaces of the main power system. Since ^{110}Ag is a long-lived radioactive fission product (half-life of 245 days); pate-out poses a radiation risk to operating personnel who may need to access components for maintenance purposes, and increases the decontamination requirements for the plant. Therefore it is important to study how ^{110}Ag can be removed from the helium coolant should it be released from the fuel spheres into helium coolant.

The objectives of this study are the following: the design and construction of an apparatus in which silver-109 atoms may be produced and deflected in a magnetic field (based on the Stern-Gerlach principle) using permanent magnets and a magnetic circuit capable of producing homogeneous and inhomogeneous magnetic fields, record the experimental results and compare them with the theoretically predicted results, and make a recommendation based, on the findings of this study, as to the possibility of removing silver-110 atoms from the helium fluid, by deflecting them with an inhomogeneous magnetic field and onto a target plate. As a preparatory study to get a better idea of the problem associated with deflection it was decided to not deflect Ag-atoms in helium but deflect them in vacuum. This was fortunate because the apparatus could then be also used for a second purpose. It could be used for a practical for a course for mechanical engineers in modern physics.

Theory

After the discovery (in 1896) of the Zeeman Effect, its theoretical interpretation confirmed that atoms have magnetic dipole moments [1]. The question remained as to whether space quantization really occurs, that is, whether the projections of the angular momentum and its associated magnetic moment on an axis defined by the direction of an imposed magnetic field are quantized. In 1921 Otto Stern proposed an experiment to answer this question. It would consist of generating a beam of silver atoms from an oven, collimating the beam with a pair of slits (0.03 mm wide) and then passing it through an inhomogeneous magnetic field, generated by permanent magnets, and observing how the beam was deflected by the force exerted by the field on the magnetic dipole moments of the atoms. The detector was a glass plate on which the silver atoms in the deflected beam would be deposited.

Stern was clumsy with his hands and never touched the apparatus of his experiments. He enlisted Walther Gerlach, a skilled experimentalist, to collaborate in the experiment [1]. Stern predicted that the effect would be just barely observable. They had difficulty in raising support in the midst of the post World War I financial turmoil in Germany. The apparatus, which required extremely precise alignment and a high vacuum, kept breaking down. Finally, after a year of struggle, they obtained an exposure of sufficient length to give promise of an observable silver spot on the glass target plate. At first, when they examined the glass plate they did not see anything. Then, gradually, the spot of Ag-atoms became visible, showing a beam separation of 0.2 millimeters [2]. Apparently, Stern could only afford cheap cigars with high sulfur content. As he puffed on the glass plate, sulfur fumes converted the invisible deposit of silver into visible black silver sulfide, and the splitting of the beam was observed. This experiment was then and subsequently called the Stern-Gerlach experiment.

Figure 1 shows the path of a Ag-atom in an inhomogeneous magnetic field. The central axis of the beam is taken as the *x* axis, and the magnetic field direction as the *z* axis as illustrated in figure 1. To calculate the distance of deflection for the atom of mass *m* and velocity *v,* it is assumed that the deflecting force is constant in the region between the pole pieces traversed by the beam, and zero elsewhere. Let Z be the distance of deflection of an atom due to the force $F_z = \mu_z \frac{\partial B}{\partial z}$ exerted during its passage between the pole pieces (where $\frac{\partial B}{\partial z}$ is the gradient of the magnetic field in the z-direction and the magnetic dipole moment μ_z = 9.270154x10^{-24} J/T), Z is then given by [1]:

$$Z = F_z \left[l_m \left(\frac{l_{mg} + \frac{l_m}{2}}{mv^2} \right) \right] \qquad (1)$$

Where l_m is the magnet length, m

l_{mg} is the distance from the edge of the magnet to the target plate.

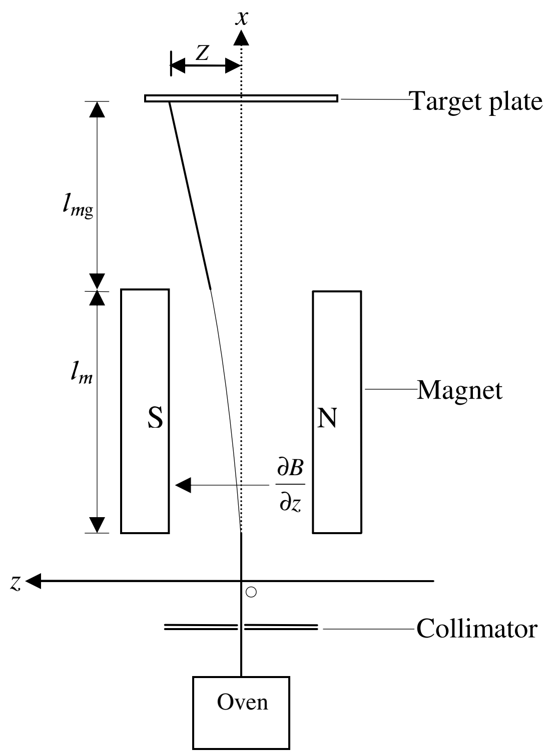


Fig 1 Path of a Ag-atom under the influence of an inhomogeneous magnetic field

Experimental apparatus

An apparatus was constructed and used to deflect the Ag-atoms in a homogeneous and inhomogeneous magnetic field. This apparatus consisted of a cylindrical vacuum chamber containing the following items: a crucible, a pair of plates with round-holes or slits in them, a magnetic circuit with a gap in which an inhomogeneous and homogeneous magnetic field could be produced, and a target plate. The crucible generated Ag-atoms by vaporizing silver-109 metal grains. Ag-atoms from the crucible were collimated with a pair plates with round-holes or slits in them, on their way to a magnetic field that was produced by the neodymium, iron-boron, NdFeB (or NIB) magnets and these Ag-atoms were deposited onto a target plate where their deflection could be investigated. Figure 2 shows a photograph of the complete experimental set-up. Figures 3 and 4 show a photograph of the vacuum chamber without and with the magnetic circuit inside.

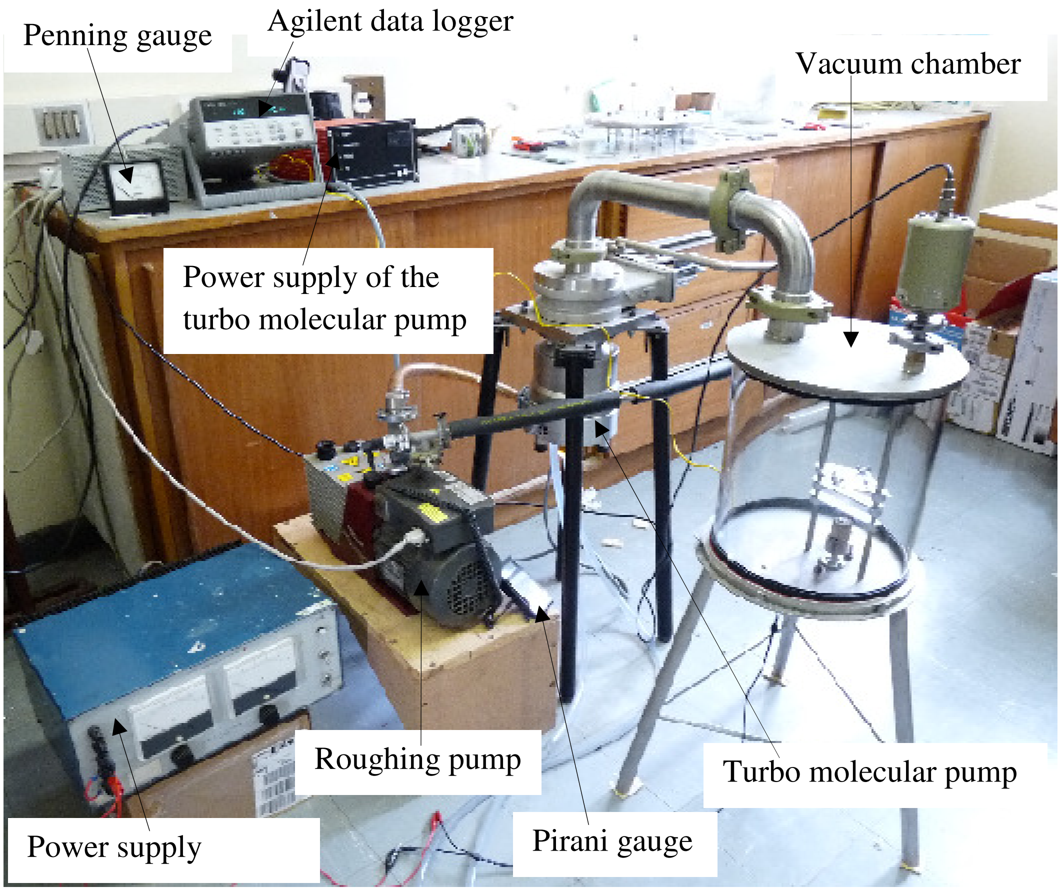


Fig 2 Photograph of the complete experimental set-up

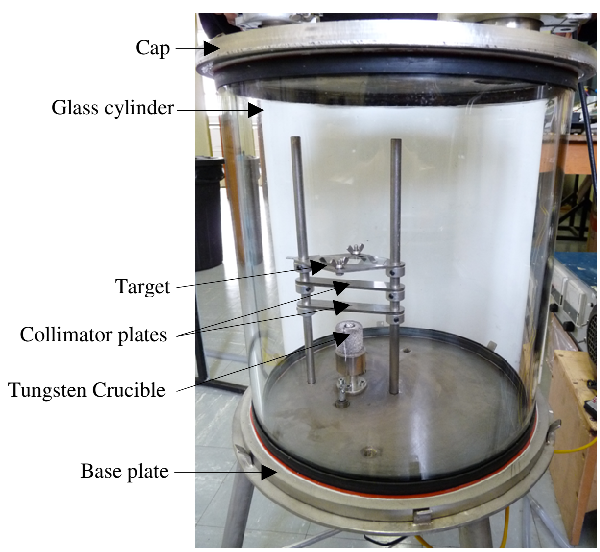


Fig 3 Cylindrical vacuum chamber (without the magnetic circuit)

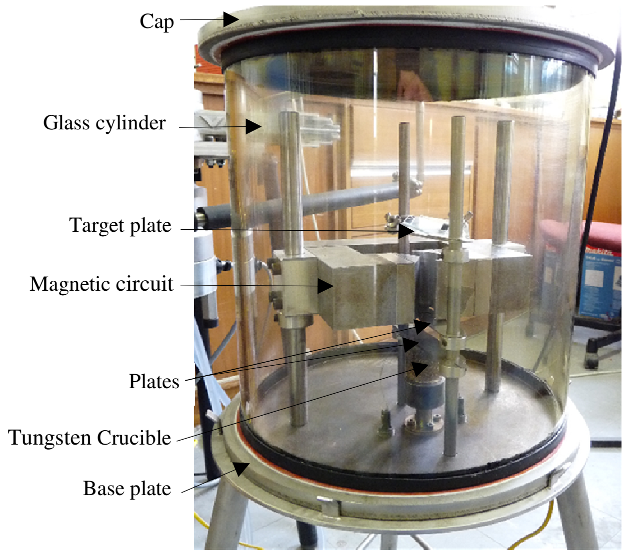


Fig 4 Cylindrical vacuum chamber (with the magnetic circuit)

The basic components of the experimental set-up include: turbo-molecular pump, roughing pump, crucible, power supply, a pair of plates with round-holes or slits in them, tungsten crucible, target plate, K-type thermocouple, Pirani gauge, Penning gauge and C-shaped iron magnetic circuit with NIB magnets. A turbo-molecular pump (model 360 manufactured by Leybold Heraeus) and a roughing pump (model 909190-2000 CVS manufactured by Galileo vacuum Tech) produced a vacuum of 1.33×10^{-5} mbar (see fig 2). A tungsten crucible (see fig 3) of 25 mm height and 5 mm inner diameter was used to vaporize silver-109 metal grains in order to generate Ag-atoms. This crucible was surrounded by a coil of tungsten wire which was connected to a DC power supply (which is discussed below) in order to heat the crucible. A 500 Watt DC power supply (model DC035-10-02 manufactured by Delta Elektronika) was used to heat the crucible (see fig 2). A pair of plates with round-holes (with a width of 1 mm) or slits (with a width of 0.5 mm and length of 6 mm) in them collimated a beam of Ag-atoms from the crucible to the magnetic field (see fig 3) that was produced by a magnetic circuit which is discussed below. For the pair of plates with round-holes in them the temperature of silver in the crucible was kept at a thermocouple temperature reading of ±1005 °C. For the pair of plates with slits in them the temperature of silver in the crucible was kept at ±1012 °C. This corresponds to the vaporization temperatures of 6.5×10^{-3} and 1.1×10^{-2} mbar, respectively [6].

A target plate was a 75x25 mm^2 glass slide and used to intercept the Ag-atoms (see fig 3). A K-type thermocouple was connected to the crucible in order to estimate the temperature of silver within the crucible. A pirani and penning gauges were used to measure the pressure in a vacuum chamber (see fig 2). A C-shaped iron magnetic circuit (see fig 3) with NIB magnets and a gap of l_g = 18 mm was capable of producing a homogeneous and inhomogeneous magnetic field in the gap. The geometry of this magnetic circuit is shown in figure 5 and it was obtained using a MagNet software [7]. In figure 5 the magnets are labeled and the lines that appear in the iron and the gap are magnetic field lines. Minimum and maximum values of the magnetic flux density B

(B_{min} and B_{max}) in the gap are also given. Point k represents the position of the beam in the gap and is 7.2 mm away from the point where B_{max} occurs. The gradient of the magnetic field at the position of the beam is 35.78 T/m.

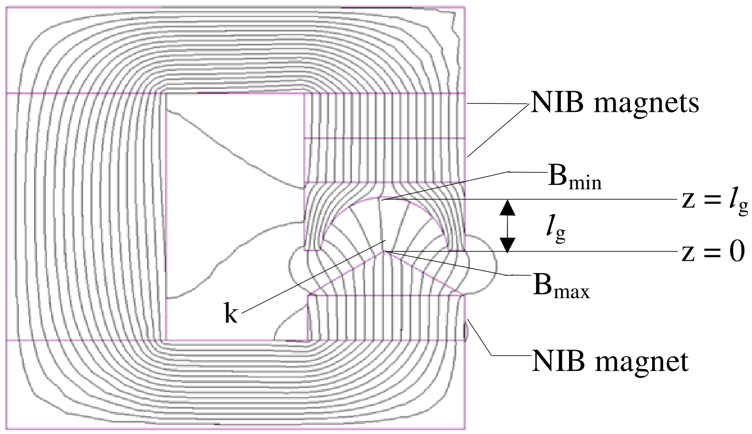


Fig 5 Soft iron magnetic circuit used in this study to create an inhomogeneous magnetic field l_g = 18 mm, B_{max} = 1.04 and B_{min} = 0.24 T

Experimental procedure

The experimental procedure is sequenced as follows:

i. Ensure that the power supply is switched off
ii. Assemble the apparatus as follows (No unauthorized person is allowed to assemble the apparatus):
    - Put the base plate of the vacuum chamber on its stand
    - Make sure that the target plate, magnetic circuit and all collimators are tightly fitted and record their distances from the crucible
    - Clean the target plate with acetone and fasten it on its holder
    - Place the glass cylinder of the vacuum chamber on the base plate
    - Fill the crucible with silver grains
    - Replace the cap of the vacuum chamber
    - Before the roughing and the turbo-molecular pump are connected to the vacuum chamber, make sure that vacuum grease is applied to every joint surface where a leak could occur
    - Connect the roughing and the turbo-molecular pump to the vacuum chamber
    - Connect the thermocouple to just touch the crucible
    - Connect a power supply to the crucible using the terminals
iii. Check the oil level of the vacuum pumps and add oil if necessary
iv. Switch on the Perani and Penning gauges
v. Switch on the roughing pump until the pressure of 1.33×10^{-3} mbar is reached

vi. Open the tap to run water for cooling the turbo-molecular pump and make sure that there are no water leaks
vii. Switch on the turbo-molecular pump when a pressure of about 1.33×10^{-3} mbar is reached
viii. Estimate the temperature of the silver in the crucible by recording the thermocouple measurement
ix. When the pressure of 1.33×10^{-5} mbar is reached, switch on the power supply to the crucible
x. Increase the current on the power supply by 2 A every 15 min until the temperature reading on the thermocouple reaches the required temperature
xi. Allow the experiment to run for 2.5 hours
xii. Switch off the power supply after the experiment has run.
xiii. Switch off the turbo-molecular pump first and only then the roughing pump
xiv. Allow the temperature reading on the thermocouple to drop to 70 °C
xv. Disassemble the apparatus as follows:
    - Disconnect the power supply from the crucible through the terminals
    - Disconnect the thermocouple from the crucible
    - Disconnect the roughing and turbo-molecular pump from the vacuum chamber
    - Remove the cap of the vacuum chamber
    - Remove the target plate from the vacuum chamber to examine the deposit of silver on the target plate
    - Remove the vacuum chamber from the stand
    - Separate the base plate and the glass cylinder of the vacuum chamber and store the glass cylinder in a safe place

Theoretical results

The deflection of Ag-atoms in an inhomogeneous magnetic field was calculated using the gradient of the magnetic field at the position of the beam being equal to 35.78 T/m, and as a function of some assumed values of the speed in order to assess how the deflection varies with speed. The calculations were performed based on figure 6. Figure 6 shows the schematic layout of the experimental set-up within the vacuum chamber showing the important dimensions.

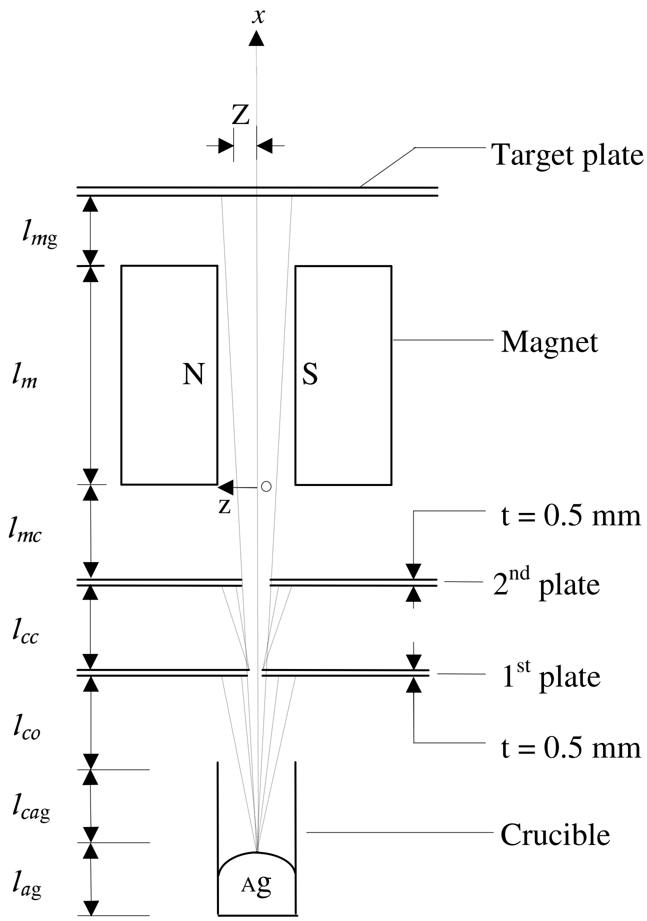


Fig 6 Schematic layout of the experimental set-up within the vacuum chamber showing the important dimensions

Table 1 shows the results for the calculations of the deflection Z of Ag-atoms that were performed for three different values of l_{mg} (distance between the target and the magnet) and as a function of the speed of the atoms v for each value of l_{mg}. These calculations were performed using the following values**:** l_{co} = 7.5 mm, l_{cc} = 2.5 mm, l_{mc} = 0 mm, l_m = 50 mm. It was assumed that the temperature T of Ag-atoms was ±1000 °C.

At v = 43 m/s, the deflection of Ag-atoms Z was found to be 1.25 mm for l_{mg} = 0 and 1.89 mm for l_{mg} = 13 mm. This means that for the magnet of 50 mm length and l_{mg} = 0 the deflection of atoms (travelling at 43 m/s) that is observed on the target plate is 0.64 mm less than the deflection that is observed if the target plate is at l_{mg} =13 mm. For the same value of v = 43 m/s the deflection Z was found to be 2.74 mm for l_{mg} = 30 mm which is 0.85 mm greater than Z for l_{mg} = 13 mm. This shows that Z increases as l_{mg} increases.

At v = 53 m/s and l_{mg} = 0 mm the deflection of Ag-atoms Z was found to be 0.82 mm. This means if Ag-atoms are travelling in an inhomogeneous magnetic field and the target plate is positioned at the end of the magnet, the deflection of Ag-atoms travelling at 53 m/s is 0.43 mm less than the deflection of Ag-atoms travelling at 43 m/s. At v = 73 m/s and l_{mg} = 0 mm the deflection of Ag-atoms Z was found to be 0.43 mm. This means if Ag-atoms are travelling in an inhomogeneous magnetic field and the target plate is positioned onto the magnet, the deflection of Ag-atoms travelling at 73 m/s is 0.39 mm less that the deflection of Ag-atoms travelling at v = 53 m/s. A similar trend applies for v = 112 m/s and 73 m/s, 135 m/s and 158 m/s and so on as seen in table 1. The same trend occurs at all three values of l_{mg}, as seen in table 1. It is therefore concluded that Ag-atoms that are travelling at low speeds are more deflected than those that are travelling at high speeds.

Table 1 Theoretically calculated deflection at l_m =50 mm for different values of l_{mg} and v using equation (1)

T (°C)	**v (m/s)**	**Z at l_{mg} = 0 mm (mm)**	**Z at l_{mg} =13 mm (mm)**	**Z at l_{mg} = 30 mm (mm)**
1000	43	1.245675325	1.893426493	2.740485714
1000	53	0.819955028	1.246331643	1.803901063
1000	73	0.432211236	0.656961078	0.950864719
1000	112	0.183613973	0.279093239	0.40395074
1000	135	0.126378802	0.19209578	0.278033365
1000	158	0.092263006	0.140239769	0.202978613
1000	181	0.070304743	0.106863209	0.154670434
1000	204	0.055345388	0.08412499	0.121759854
1000	227	0.044698202	0.067941268	0.098336045
1000	250	0.036852059	0.056015129	0.081074529
1000	273	0.030904127	0.046974273	0.067989079
1000	296	0.026288049	0.039957834	0.057833707
1000	319	0.022633953	0.034403608	0.049794696
1000	342	0.019691988	0.029931822	0.043322373
1000	365	0.017288449	0.026278443	0.038034589
1000	388	0.015299538	0.023255298	0.033658984
1000	411	0.013635094	0.020725343	0.029997206
1000	434	0.012228194	0.018586855	0.026902026
1000	457	0.01102832	0.016763047	0.024262305
1000	480	0.009996761	0.015195076	0.021992874

Figure 7 shows a graphical representation of the results that are shown in table 1.This figure shows the deflection Z of the atoms as a function of speed for increasing distances between the magnet and the target plate. A comparison of the deflections obtained at each spacing between the magnet and the target l_{mg}, shows that the greatest deflection is achieved at the furthest spacing (l_{mg}= 30 mm), and decreasing the spacing decreases the deflection achieved. At all three values of l_{mg} the deflection decreases as the speed increases. The maximum deflection is therefore achieved at the lowest speed and furthest distance between the magnet and the target plate.

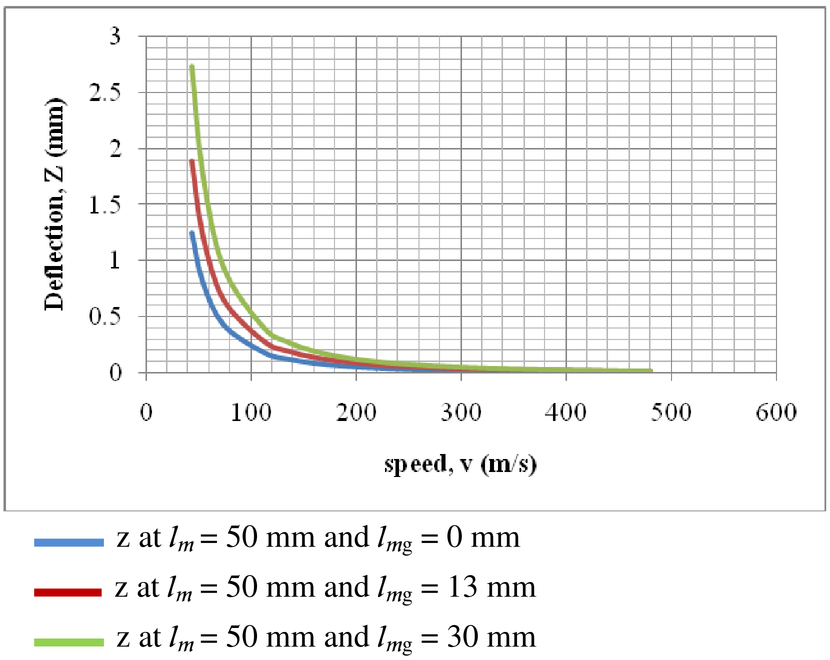


Fig 7 Deflection of Ag-atoms for different values of l_{mg}

Experimental results

The experimental results for the deflection of Ag-atoms are shown in figures 8 to 10. Figures 8 and 9 show the silver deposits that were observed on the glass slides when Ag-atoms were collimated using a pair of plates with round-holes in them. Figure 10 shows the silver deposits that was observed when Ag-atoms were collimated with a pair of plates with slits in them. The glass slides were coated with gold because without this there was no clear boundary on the edge of each deposit of silver, making it difficult to measure the deposit width. The left hand images in figures 8 and 9 are the original photographs, while the images on the right are the same photograph but has been highlighted with circles in an attempt to more clearly quantify the results.

Figures 8 (a), 9 (a) and 10 (a) show the deposits of silver that were observed when the atoms were not subjected to a magnetic field, for the reference purpose. Figures 8 (b), 9 (b) and 10 (b) show the deposits of Ag-atoms that were observed when they were acted upon by the homogeneous magnetic field before they reached the target plate. Figures 8 (c), 9 (c) and 10 (c) show the deposits of Ag-atoms that were observed when they were acted upon by an inhomogeneous magnetic field. The width of each deposit is indicated on its corresponding highlighted-deposit as seen in figures 8, 9 and 10.

In figure 8 the deposit (b) is (4.7 - 4) = 0.7 mm wider than the reference deposit (a). This means that the maximum deflection caused by the homogeneous magnetic field with the target 13 mm from the magnet and the beam collimated by a pair of plates with round-holes in them is 0.7/2 = 0.35 mm from the centre. The maximum deflections, as similarly determined are summarized in table 2.

Table 2 Deflection of silver atoms when the target plate was position 13 mm away from magnet

Spot	(a)	(b)	(c)
Deflection	0	0.35 mm	1.95mm

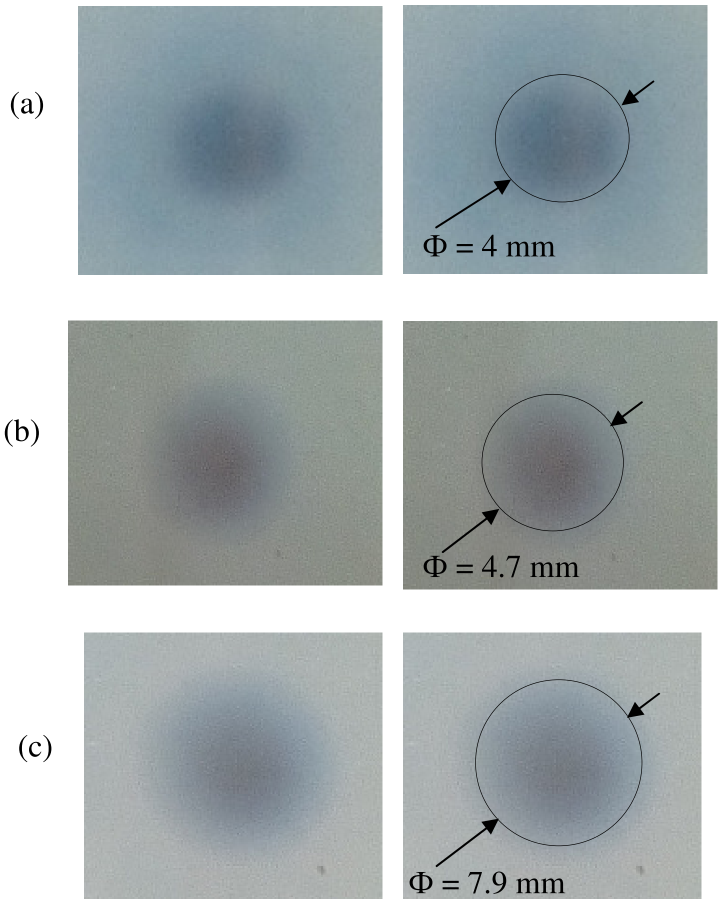


Fig 8 The spots of Ag-atoms at 13 mm away from the magnet

Table 3 shows the maximum deflections of silver atoms when the target plate was positioned 30 mm away from the end of the magnet and they were calculated using the results shown in figure 9 and the same method that is used to calculate those in table 2.

Table 3 Deflection of silver atoms when the target plate was position 30 mm away from magnet

Spot	(a)	(b)	(c)
Deflection	0	0.55 mm	2.875mm

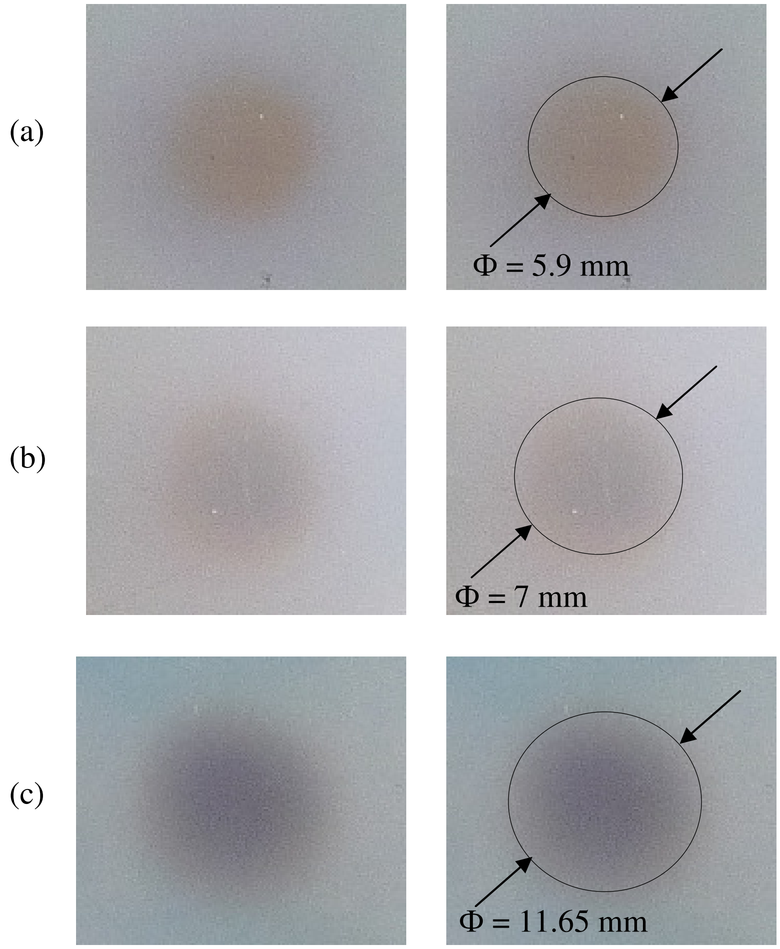
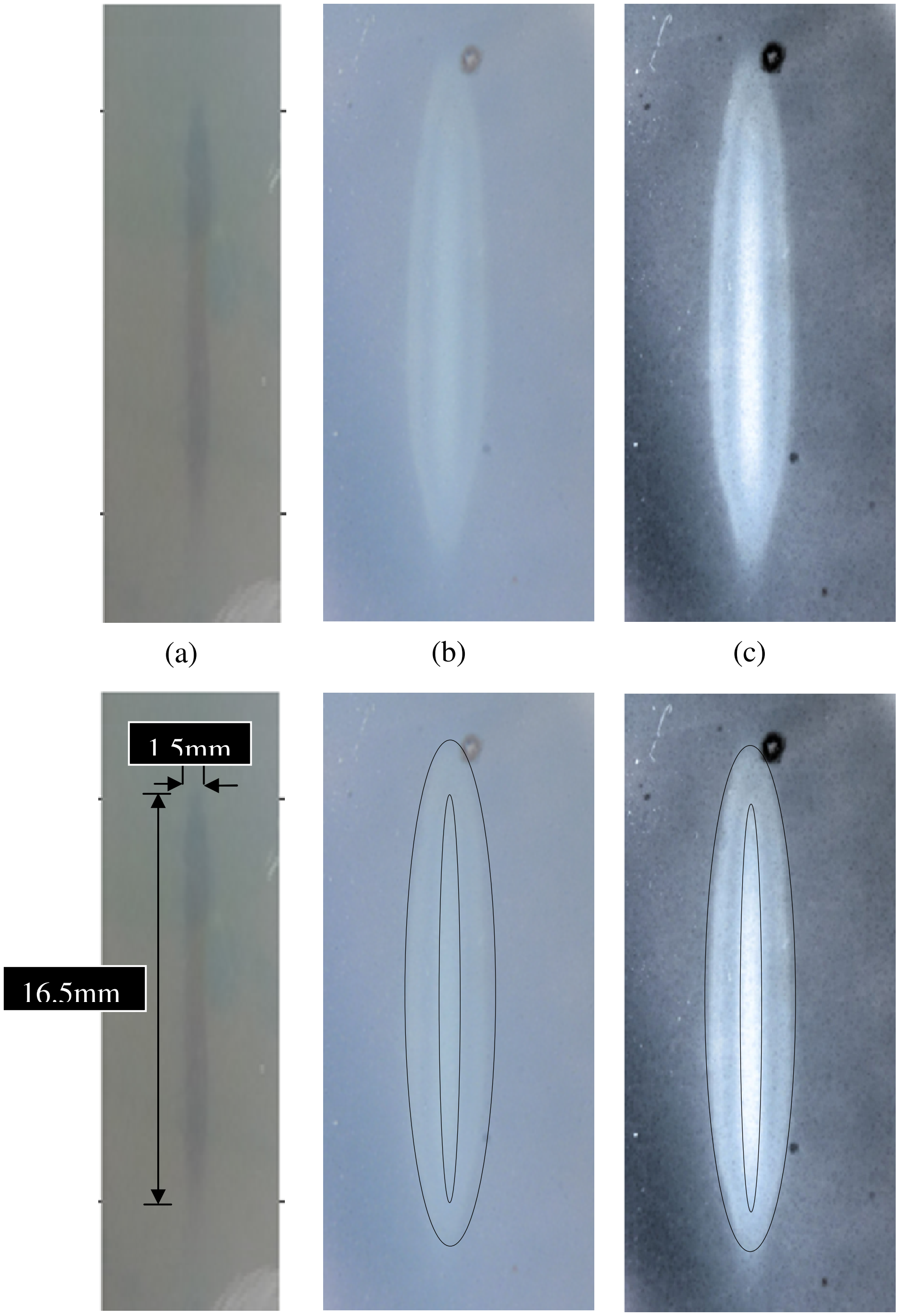


Fig 9 The spots of Ag-atoms at 30 mm away from the magnet

In figure 10 the reference deposit (a) shows a linear shape showing that Ag-atoms were collimated with a pair of plates with slits in them. A width of this line is 1.5 mm and its length is 16.5 mm. The deposit (b) of Ag-atoms that was observed when they were acted upon by the inhomogeneous magnetic field figures 10 (b) and (e) shows a roughly ellipical shape. This means that a linear shape of the beam of Ag-atoms changed to an ellipical shape when the atoms were acted upon by an inhomogeneous magnetic field. However the beam of Ag-atoms did not split completely into two separate beams. It is because the beam consisted of atoms with different speeds. The atoms with different speeds experienced different deflections the faster the speed the less the deflection. Figure 10 (c) shows the image of figure 10 (b) after it has been colur-only enhanced with Autodesk Inventor Professional 2009 software, which makes the elliptical deposit somewhat more clearly visible.

The image of the silver deposit in figure 10 (c) was then clearly seen and is shown in figure 11 (a). The drawing with the dimensions of this image is given in figure 11 (b). Figures 10 (d), 10 (e) and 10 (f) are highlighted photographs of figures 10 (a), 10 (b) and 10 (c), respectively. These photographs are highlighted to show the effects more clearly.



(d) (e) (f)

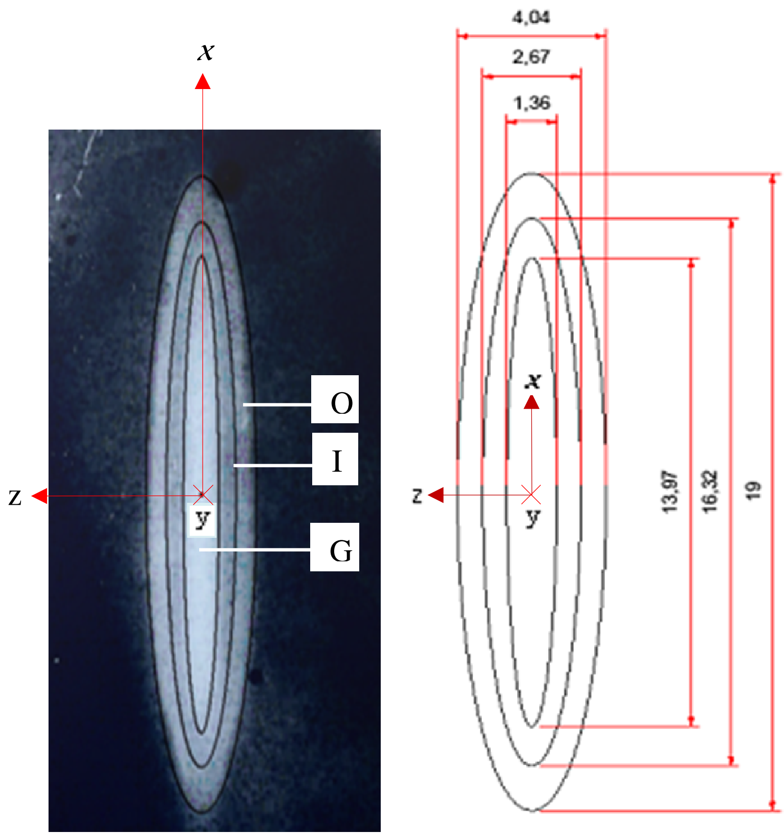
No magnetic field

Inhomogeneous magnetic field

Image (a) after it has been enhanced with Autodesk Inventor Professional 2009 software

Fig 10 Deposits of Ag-atoms from the slit collimator when glass slides and a target plate was positioned 13 mm away from magnet

The deflection of atoms was calculated using the dimensions of the elliptical deposit shown in figure 11 (b) and the dimensions of the corresponing reference deposit shown in figure 10 (d). The maximum deflection of Ag-atoms in the positive and negative z direction (that is towards B_{max} and towards B_{min}) is (4.04 - 1.5)/2 = 1.27 mm and maximum deflection of Ag-atoms towards the positive and negative *x* direction is (19 - 16.5)/2 = 1.25 mm.



a) Colour enhanced image

b) Dimensions (mm) of the elliptical rings shown on a)

Fig 11 Colour enhanced images of the elliptical deposit

Discussion, conclusion and recommendation

Collimating Ag-atoms with a pair of round holes showed the following: the maximum deflection of Ag-atoms due to an inhomogeneous magnetic field is 1.95 and 2.88 mm when the distance between the magnet and the target was 13 and 30 mm, respectively. The deflections 1.95 and 2.88 mm are 3.17 % and 4.93 % greater than the theoretically predicted deflections of 1.89 and 2.74 mm that were found for the atoms travelling at 43 mm/s, distances between the target plate and the magnet are 13 and 30 mm, respectively.

Collimating Ag-atoms with a pair of slits showed the following: the maximum deflection of Ag-atoms due an inhomogeneous magnetic field and with the target plate positioned 13 mm away from magnet is 1.27 mm towards the positive and negative z-axis, and 1.25 mm towards the positive and negative *x*-axis. The deflections 1.27 and 1.25 mm are 2.36 % and 0.8 % greater than 2.4 mm (a deflection that was theoretically predicted for atoms travelling at 53 m/s in the same experimental configuration), respectively.

It is therefore concluded that the experimental results are in agreement with the theoretical results; and the apparatus can be used for a practical for a course in modern physics. The experimental results (figures 8, 9, 10 and 11) showed that neither homogeneous nor inhomogeneous magnetic fields were able to split a beam of Ag-atoms completely into separate beams, in a vacuum of 1.33×10^{-5} mbar. This shows that it will be even more difficult for an inhomogeneous magnetic field to split Ag-atoms in helium because Ag-atoms have a shorter mean free path in helium than vacuum. It is therefore finally concluded that a proposed technique of removing Ag-atoms from helium fluid by deflecting these Ag-atoms with an inhomogeneous magnetic field onto a target plate situated on the inner perimeter of the helium pipe may not be effective in remaining silver from the helium from a PBMR coolant stream. A recommendation is that further research be done to find a means of ionizing Ag-atoms in helium so that they can be removed with an electric field, rather.

Acknowledgments

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