Francis Aston and the mass spectrograph

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The chemical determination of atomic weights gives the average weight for an aggregate of a large number of atoms. Although this is useful in many applications, the determination of the masses of individual atoms gives further important information, in particular the stability of the atoms or more precisely of their nuclei. The first accurate determination of the masses of individual atoms was made by Aston in 1919. His measurements demonstrated the existence of isotopes in non-radioactive elements and paved the way for our present picture of the nuclear atom.

Historical background to Aston’s work

To appreciate the significance of the work Thomson was doing and Aston’s subsequent role we need to go back in the history of chemistry. In 1803 John Dalton put forward an atomic theory, which laid the foundations of modern chemistry. One of the postulates was that atoms of the same element are similar to one another and equal in weight. About ten years later William Prout suggested that the atoms of the elements were made up of aggregates of hydrogen atoms. If this were true the weights of atoms would be expressed as whole numbers, i.e. integers, and, on the basis of Dalton’s postulate that all the atoms of an element had the same weight, atomic weights would also be whole numbers. However, experiment showed that although the atomic weights of many of the elements were whole numbers, far more than could be attributed to chance, there were a few, for example, magnesium, atomic weight 24.3, and chlorine, atomic weight 35.5, which were not. Therefore, Dalton and Prout could not both be correct, and around 1900 it was for the post. Aston accepted the invitation and thus began a career that had momentous consequences for chemistry and nuclear physics.

Early life

Francis William Aston was born on 1 September 1877 at Harborne, Birmingham. He was the third child of a family of seven. His father and paternal grandfather were metal merchants and farmers, and Francis was brought up on a small farm. From an early age he showed a keen interest in mechanical toys and scientific apparatus. He had a ‘laboratory’ on a stable and amused his sisters with home-made fireworks and large tissue-paper hot-air balloons. These were dispatched with stamped addressed postcards, which were sometimes returned from great distances.

Aston entered Malvern College in September 1891 and two years later went to Mason College (which subsequently became the University of Birmingham), where he studied chemistry and physics. The professor in physics was John Poynting (of Poynting’s vector). While at Birmingham Aston acquired skill with tools and glass-blowing which proved invaluable in his later work. Faced with the need to earn a living after graduating he took a course in fermentation chemistry and in 1900 started work in a brewery in Wolverhampton. In his spare time he experimented at home, designing and building new forms of Sprengel and Töpler vacuum pumps. This experience was again to stand him in good stead later on.

In 1903 Aston returned to Birmingham University and physics. He worked on the properties of electrical discharges in gases and measured the variation of the length of the Crookes dark space with current and pressure. In 1906 his father died, and he used a legacy to travel round the world. On his return he was appointed a lecturer in Birmingham University, but after one term he received an invitation from Joseph (J. J.) Thomson to come to the Cavendish Laboratory at Cambridge as his assistant. Poynting, a close friend of Thomson, had recognised Aston’s great gifts as an experimenter and recommended him for the post. Aston accepted the invitation and thus began a career that had momentous consequences for chemistry and nuclear physics.

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Thomas’s work on positive rays

In 1886 Eugen Goldstein was investigating the properties of the electric discharge obtained when a large voltage is applied across a pair of electrodes in a vessel containing a gas at low pressure. He found that if a channel or canal was cut through the cathode a beam of light appeared on the side remote from the anode. He called the beam Kanalstrahlen, canal rays. In
1898 Willy Wien managed to deflect the beam with a strong magnetic field, in a direction which showed it was due to a stream of positively charged particles. They are in fact the positive ions resulting from the atoms in the gas that have lost one or more electrons. In 1907 Thomson started to investigate the positive rays. He measured the mass of the particles by deflecting the rays with electric and magnetic fields. His apparatus was the forerunner of Aston’s mass spectrograph and it is instructive to consider it first.

The essentials of the apparatus are shown in Fig. 1. The discharge occurs in the spherical tube T. The anode A is located in a side arm, and the positive rays pass through the cathode C, which is a fine tube. The rays then pass between the poles N and S of an electromagnet, the pole pieces P₁, P₂ of which are insulated from the magnet by thin sheets of mica. By this means a potential difference may be applied across the pole pieces, giving an electric field E in the same direction as the magnetic field B, this direction being at right angles to the path of the particles. The particles finally strike the screen H, where they produce a fluorescent spot. In the absence of the two fields the particles travel in a straight line, and the spot is in the centre of the screen in line with the fine tube in the cathode.

Take a set of right-handed axes x, y, z, with the initial direction of the particles as the z axis, and the common direction of E and B as the x axis. We consider the electric and magnetic deflections separately. The deflection produced by the electric field is shown by the diagram in Fig. 2. The particles coming from the left with velocity v enter the region between the pole pieces P₁ and P₂, across which a potential difference V is applied. If the pole pieces are a distance d apart this gives an electric field \( E = V/d \), which causes an acceleration \( eE/m \), where \( e \) is the charge and \( m \) the mass of the particles. If \( l_p \) is the length of the plates, the particles spend an approximate time \( l_p/v \) between the plates, and when they emerge from the plates they have acquired a component of velocity in the x direction given by

\[
v_x = eEId/mv. \tag{1}\]

Since \( v_x \ll v \), the angle through which the particles are deflected by the field is approximately

\[
\theta = \frac{v_x}{v} = \frac{eEId}{mv^2}. \tag{2}\]

A magnetic field B whose direction is at right angles to the path of the particles deflects them into a circular path of radius \( R \) as shown in Fig. 3. The force due to B is \( Bev \), and its direction is at right angles to the directions of both B and v. The acceleration in the circular path is \( e^2B^2/m \). Thus

\[
mv^2/R = Bev, \quad i.e. \quad mv = BeR. \tag{3}\]

\[
\theta = \frac{eEId}{mv^2} B = \frac{eEId}{mv}B. \tag{4}\]

\[
where \ l_p \ is \ the \ length \ of \ the \ path \ in \ the \ magnetic \ field. \]

Now let E and B act together. The screen H, which contains the x and y axes, is shown in Fig. 4, with the position O of the spot for the undeflected beam as the origin. The field E deflects the particles in the x direction by an amount proportional to the angle \( \theta \), while B deflects them in the y direction by an amount proportional to the angle \( \phi \), both the angles being small. The coordinates of the spot are therefore

\[
x = c_1 \frac{eEId}{mv^2} B, \quad y = c_1 \frac{eBId}{mv} B. \tag{5}\]

\[
where \ c_1 \ and \ c_2 \ are \ constants \ depending \ on \ the \ geometry \ of \ the \ apparatus. \]

Eliminating the velocity \( v \) between these two expressions gives

\[
x/c_1 = \frac{eEId}{mv^2} \quad \Rightarrow \quad \frac{x^2}{c_1} = \frac{eB^2}{mE}. \tag{6}\]

\[
where \ the \ constant \ c_1 \ depends \ on \ the \ geometry \ of \ the \ apparatus. \ Thus, \ for \ a \ beam \ of \ ions \ with \ the \ same \ value \ of \ elm \ and \ varying \ velocities, \ the \ pattern \ on \ the \ screen \ is \ a \ parabola, \ Fig. 4. \]
traces. If the mass is known for one of the parabolas, measurements of the \( y \) values at constant \( x \) give the values of all the other masses. The axis \( O \alpha \) is not marked on the photograph. The magnetic field is therefore reversed for the second half of the exposure, which puts the pattern in the \( -y \) region and allows the \( y \) values to be measured.

When Aston arrived at the Cavendish Laboratory in 1909 Thomson’s positive ray apparatus was already working. With his assistance the apparatus was greatly improved, and by 1912 parabolas corresponding to mass differences of 10% could be resolved. In November of that year some gas containing neon was analysed. The photograph, Fig. 5, showed a strong parabola corresponding to a mass of 20 (on the scale oxygen = 16) and a much weaker one at a mass of 22. Various possibilities for the 22 parabola were considered. One was that it was due to doubly charged CO\(_2\). However, when the gas was passed through liquid air, the parabola at 44, due to singly charged CO\(_2\), disappeared, while the one at 22 was not affected. Another speculation was that the 22 trace was due to a compound NeH\(_2\).

From density measurements the atomic weight of neon was known to be 20.2. So the novel, and at the time revolutionary, suggestion was made that neon could exist in two forms, which were isotopes, just like the isotopes suggested by Soddy in radioactive elements. If the isotope of mass 20 was 9 times more abundant than the one of mass 22, that would give the measured atomic weight of 20.2. In other words, neon did not consist of identical atoms of mass 20.2, but of two different atoms of mass 20 and 22, in line with Prout’s hypothesis.

Aston set to work to see if he could separate the two constituents of neon. He first tried fractional distillation, but without success. He then tried diffusion through fine pores, using clay tobacco pipes, and after much labour obtained a small yield of neon. After much labour obtained a small yield of neon. However, undeterred, he carried on with the heaviest fraction and ultimately obtained two samples with densities 20.15 and 20.28 on the scale \( O_2 = 32 \). These results were just on the borderline of the experimental uncertainty.

The work was interrupted by the first World War. Aston was sent to the Royal Aircraft Factory, later the Royal Aircraft Establishment, at Farnborough. Frederick Lindemann, later Lord Cherwell, and George Thomson (J. J. Thomson’s son) were also there. In after years Thomson recollected that Lindemann was sceptical of Aston’s isotope hypothesis, preferring the idea of CO\(_2\) or NeH\(_2\) for the 22 parabola. He said that Lindemann was a much better theoretician than Aston and always won the argument, but Aston ‘had faith and next morning was still of the same opinion’. In 1914 Aston crashed in an experimental aeroplane, but escaped unhurt. He worked at Farnborough as a chemist, studying among other things the properties of the doped canvas with which aeroplanes were then covered.

### Aston’s first mass spectrograph

After the war Aston returned to the Cavendish Laboratory. While at Farnborough he had meditated on an improved form of the apparatus to measure the masses of the positive ions, and in 1919 he built his first mass spectrograph. Like Thomson’s parabola apparatus it employed electric and magnetic fields to deflect the particles, but the two fields were in different regions along the path of the particles. Unlike Thomson’s apparatus in which particles with the same \( \text{elm} \) value, but different velocities, were distributed along the parabola, in Aston’s spectrograph these particles were focused to the same point on the screen. This was a big advantage. The focused beam was much more intense, thus permitting finer slits to be used, which improved the resolution and accuracy of the instrument.

The principle of the instrument is illustrated in Fig. 6. The path of the positive particles emerging from the discharge tube is defined by a pair of narrow slits \( S_1 \) and \( S_2 \). The particles then pass between a pair of plates \( P_1 \) and \( P_2 \) across which a potential difference is applied. The particles are deflected downwards by the electric field towards the negative plate \( P_2 \). They are deflected continuously in the region between the plates, but as a first approximation we may assume that the paths come from a point \( Z \) in the middle of the plates on the line defined by \( S_1 \) and \( S_2 \). A group of the rays is allowed to pass through a narrow diaphragm \( D \), which selects those deflected through angles between \( \theta \) and \( \theta + \delta \theta \). Then, they pass between the poles of an electromagnet which has its north pole above the plane of the diagram. This deflects the particles in the opposite direction to that of the electric field.

The same notation is used as in the discussion of Thomson’s apparatus. Eqs. (2) and (4) still apply. For particles of velocity \( v \), charge \( e \) and mass \( m \), the electric field \( E \) gives a deflection \( \theta \), and the magnetic field \( B \) gives a deflection \( \phi \). The position of the diaphragm \( D \) fixes the angle \( \theta \) and hence the velocity of the particles passing through. The spread \( \delta \theta \) in \( \theta \) gives rise to a spread \( \delta \phi \) in \( \phi \), which in turn gives a spread in the deflection produced by the magnetic field. The relations between \( \theta, \phi \) and \( \delta \theta, \delta \phi \) are obtained from eqns. (2) and (4). For a constant value...
of $\varepsilon m$, $\theta$ is proportional to $1/h^2$, and $\varphi$ is proportional to $1/v$. Therefore

$$\delta \theta = -2 \frac{\delta \varepsilon}{v}, \quad \delta \varphi = \frac{\delta \varepsilon}{v}, \quad \delta \rho = \varphi \delta \theta,$$

whence

$$\delta \rho/\delta \theta = \varphi/20.$$

The minus signs in eqns. (7) indicate that the faster particles, indicated by the blue path in Fig. 6, are deflected less in both the electric and the magnetic fields than the slower particles indicated in red. Since the electric and magnetic deflections are in opposite directions the rays passing through D are brought together at a point F.

It is readily shown that the angle between the line ZF and the initial direction ZC of the particles is equal to $\theta$. Fig. 7 shows the mean paths of the particles. The angle between FZ and OZ is denoted by $\rho$, where O is the centre of the magnetic field.

The position of the focus point on the line ZB for a given $\varepsilon m$ value may be calculated from the values of $E$, $B$, and the geometry of the apparatus. However, the quantities required are the ratios of masses, and these are obtained most accurately by empirical methods. Aston first calibrated the instrument using a set of lines given by atoms and compounds with masses spread over a suitable range, and whose relative masses were known to the accuracy required. An example of such a set was: 6, C$^2$; 8, O$^1$; 12, C; 16, O; 28, CO; 32, O$_2$; 44, CO$_2$ (The integer before each atom or compound is the effective mass number, i.e. the actual mass number divided by the number of charges on the ion.) This provided a set of points on a calibration curve. He filled in the gaps between the calibration points by a single spectrum with the same set of ions, which were made to give lines at a different place by changing the value of the magnetic field.

Aston gave a preliminary account of the spectrograph in August 1919. The instrument was an immediate success. The two isotopes of neon, mass 20 and 22, were easily resolved. Similarly, chlorine was found to be a mixture of isotopes of mass 35 and 37. By the time his first book Isotopes appeared in 1922 he had studied 27 elements. Among them were the following (masses, where oxygen is 16, in parentheses): lithium (7, 6), boron (11, 10), magnesium (24, 25, 26), argon (40, 36), krypton (84, 86, 82, 83, 80, 78) and xenon (129, 132, 131, 134, 136, 128, 130). The isotopes are given in the order of the intensities of the lines. Reproductions of the spectra for neon and chlorine are given in Fig. 8.

Although the discovery of many isotopes in light non-radioactive elements was of great importance, even more significant was Aston’s result that the masses of all the particles are whole numbers. The only exception was Aston’s result that the masses of all the particles are whole numbers. The only exception was that of hydrogen whose mass was 1.008, see below. This whole number rule as it was called gave a simple model for the atomic nucleus. The only particles known at the time were the proton and the electron, with relative masses of 1837. It was therefore proposed that the nucleus of an isotope of mass $M$ and charge $Z$, both being integers, consisted of $M$ protons and $M - Z$ electrons. Thus, for example, the nucleus of $^7$Li consisted of 7 protons and 4 electrons, while that of $^4$Li consisted of 6 protons and 3 electrons. Although this model gave the correct mass and charge of the nucleus, and satisfied the whole number rule, it had two grave defects. First, from the uncertainty principle, if an electron were confined to a region as small as an atomic nucleus, its momentum and hence energy would be much larger than the binding energy of the nucleus. Secondly, the spins of some of the nuclei were anomalous on this model. For example, the nucleus of $^14$N would consist of 14 protons and 7 electrons, giving a total of 21 particles. Since the spin of both the proton and the electron is $\frac{1}{2}$, the spin of the nucleus with an odd number of particles would be half-integral; in fact the spin of $^14$N is 1.

The discovery of the neutron by James Chadwick in 1932 removed these difficulties. The present model is that a nucleus of charge $Z$ and mass number $M$ contains $Z$ protons and $M - Z$ neutrons. Isotopes are thus nuclei with the same number of protons and a different number of neutrons. They have the same chemical properties, but different nuclear properties.
There are no electrons in the nucleus, and the nucleus \(^{14}\text{N}\) contains 14, an even number, of particles of spin \(\frac{1}{2}\).

Aston’s first mass spectrograph could separate particles with a mass difference of \(1\%\), which may be compared with a value of about 1 in 10 for Thomson’s parabola apparatus. The values of the masses were obtained with an accuracy of about 1 part in 1000.

The second and third mass spectrographs

Aston and other scientists soon grasped the reason for the departure of the mass value of hydrogen from an integral value, namely that it is the only atom with a non-composite nucleus. The masses of all the other atoms are reduced owing to the binding energy of their constituents, which results in hydrogen having a slightly higher mass relative to its mass number. The next step in mass spectrometry was therefore to improve the accuracy of the instrument to measure divergences from the whole number rule for all the atoms, which would give basic information on the binding forces within nuclei. For nuclei with mass numbers greater than about 20, the binding energy per nucleon is roughly constant, with a value between 8 and 9 MeV, which is about 1/4 of the energy equivalent of the mass of a nucleon. So to determine the mass of a nucleus with an accuracy of about 1 in 1000, the mass of the nucleus must be measured to an accuracy of about 1 part in 10\(^4\). Aston started designing an improved version of his spectrograph in 1921, though he continued to use the original instrument until it was dismantled in 1925.

In the second mass spectrograph finer slits were used and they were placed farther apart, thus more accurately defining the paths of the particles.\(^{17}\) The electric deflecting plates were curved, so that the particles remained midway between them as they were deflected. The electric deflection \(\theta\) was doubled to 1/6 rad. The potential for the deflection came from a set of 500 accumulators, each one built by Aston himself. They were charged twice a year and gave a voltage constant to better than 1 part in 10\(^5\) during a single experiment. To achieve a constant magnetic field with minimum heating, the core of the magnet was wound with over 6000 turns of wire weighing over 100 kg. A current of 1 A through the coils produced a magnetic field of 1.6 T, which was sufficient to deflect the heaviest and most energetic particles through an angle \(\phi\) of 2/3 rad. (A detailed calculation shows that, when \(\phi = 4\theta\), the position of the line varies linearly with mass, which is convenient for interpolation.) The pole pieces of the magnet were dismantled in 1925.

Aston’s third mass spectrograph in 1937 incorporated further improvements.\(^{18}\) The widths of the collimating slits could be adjusted externally, obviating the laborious opening of the apparatus which was necessary for such adjustments in the first two instruments. The stability of the magnetic field was improved by monitoring its strength with a fluxmeter; in the previous instruments only the exciting current had been kept constant. Any variation in the magnetic field was compensated for by manual adjustment of a spiral mercury resistor. Another advance was in the greatly improved sensitivity of the photographic plates used to record the lines, which resulted after extensive trials carried out with the collaboration of the Ilford photographic company.

The biggest advance came in the use of the doublet method for comparing two masses. This consists of measuring the small difference in the masses of two ions with the same mass number \(M\). The mass of an atom \(X\) with mass number \(M\) is denoted by \(m^{(M)}X\). Since the value of \(m\) is close to the integer \(M\), we may express it as

\[
m^{(M)}X = M(1 + \delta),
\]

where \(\delta\), known as the *packing fraction*, is small compared to 1.

As an example we show how Aston measured the mass of the hydrogen atom in terms of the mass of the carbon atom. He measured the difference in mass \(\Delta_1\) between the deuterium atom and the hydrogen molecule (doublet with \(M = 2\)), and the difference \(\Delta_2\) between the masses of the triatomic deuterium molecule and the doubly charged carbon atom (doublet with \(M = 6\)). Then

\[
\Delta_1 = 2m^{(1)}H - m^{(1)}H = \frac{2(1 + \delta_H) - 2(1 + \delta_D) = 2\delta_H - 2\delta_D,}{(14)}
\]

\[
\Delta_2 = 3m^{(1)}H - m^{(12}C^{2+}) = \frac{6(1 + \delta_D) - 6(1 + \delta_{12}C) = 6\delta_D - 6\delta_{12}C,}{(15)}
\]

\[
\delta_H - \delta_{12}C = (3\Delta_1 + \Delta_2)/6. \quad (16)
\]

Aston’s values for \(\Delta_1\) and \(\Delta_2\) were \((15.2 \pm 0.4) \times 10^{-4}\) and \((426.1 \pm 1.8) \times 10^{-4}\) respectively, giving \(\delta_H - \delta_{12}C = (78.2 \pm 0.4) \times 10^{-4}\).

At the time of Aston’s measurements the atomic mass unit, denoted by \(u\), was defined by taking the mass of the atom \(^{16}\text{O}\) to be exactly 16, but in 1962 the definition was changed\(^{26}\) so that the mass of the atom \(^{12}\text{C}\) is taken as exactly 12, i.e. \(\delta_{12}C = 0\). Thus on the present scale Aston’s value for the packing fraction of hydrogen was \(\delta_H = (78.2 \pm 0.4) \times 10^{-4}\), giving \(m^{(1)}H = 1.00782 \pm 0.00004\ u\). The example shows the intrinsic advantage of the method of measuring the difference in mass of doublets with the same mass number. The mass differences \(\Delta_1\) and \(\Delta_2\) are measured to accuracies of the order of 1%, but the mass of the hydrogen atom obtained is accurate to 4 parts in 10\(^5\). It may be noted that Aston’s value is in complete agreement with the present value,\(^{21}\) \(m^{(1)}H = 1.00782504 \pm 0.00000001\ u\).

The particles whose masses are measured in the spectrograph are ions that have lost one or more electrons, but the mass values quoted relate to the neutral atoms, i.e. the mass of one or more electrons is added to the measured masses. The mass of the electron, 5.486 \times 10^{-4} u, is small but not negligible in the accuracy of Aston’s measurements. On the other hand, the binding energies of the atoms in a molecule, being of the order of electronvolts, correspond to mass values of the order of 10\(^{-9}\) u. So the mass of a diatomic molecule such as hydrogen may be taken to be twice the mass of the hydrogen atom.

Aston improved the resolving power of his spectrographs from 130 for the first instrument to 600 for the second and 2000 for the third. He claimed an accuracy of 1 in 10\(^4\) for the second instrument and approaching 1 in 10\(^5\) for the third. If we compare his mass values (changing them to the \(^{12}\text{C}\) scale) with the present-day values, which are accurate to about 1 in 10\(^5\) or better, the differences for the values obtained from the 1927 instrument are on average about 1.5 in 10\(^4\), and for the 1937 values about 2.5 in 10\(^5\). So his claimed accuracy is well substantiated. The third mass spectrograph, without the magnetic field components, is in the Museum of the Cavendish Laboratory; it is shown in Fig. 9. Aston’s first mass spectrograph is in the Science Museum in South Kensington.

Other workers and modern developments

Although Aston is recognised as the pioneer in mass spectroscopy there were other major workers in the field from 1918 onwards. Arthur Dempster, at the University of Chicago, con-

constructed a mass spectrograph in 1918\textsuperscript{22} and in the next few years found isotopes in magnesium, lithium, potassium, calcium and zinc. His instrument involved bending monoenergetic ions into a semicircular path by a uniform magnetic field, which gives direction focusing, \textit{i.e.} ions diverging in direction at the entrance to the magnetic field are brought to a focus after completing a semicircle. Kenneth Bainbridge, at the Franklin Institute, Swarthmore, improved on Dempster’s instrument by using a velocity filter before the magnetic analyser, thereby removing the need for a monoenergetic source.\textsuperscript{23} With his apparatus he made the first measurement of the mass of the deuterium atom\textsuperscript{24} and also provided one of the first experimental demonstrations of Einstein’s mass-energy relation.\textsuperscript{25}

The detailed motions of ions in electric and magnetic fields were calculated by Richard Herzog and Josef Mattauch in Vienna\textsuperscript{26} and others in the early thirties. The results led to the design of high-resolution double-focusing instruments in which ions with both a spread in velocities and a spread in initial directions were brought to a focus. Instruments making use of double focusing were built by Alfred Nier at the University of Minnesota\textsuperscript{27} and several other workers.\textsuperscript{28} Further improvements came from replacing photographic plates by electrical detectors and from advances in vacuum technology.\textsuperscript{29} The value of 2000 for the resolving power of Aston’s third mass spectrograph has been extended to values exceeding $10^5$, and accuracies of the order of 1 part in 10$^8$ or 10$^9$ have been obtained.\textsuperscript{30}

Mass spectroscopy is now applied in several branches of chemistry, biology, geology, and physics. In many of these applications the classical method of electrostatic and magnetic deflection described in this paper has been replaced by timing methods. The highest precisions are obtained by cyclotron resonance in which the frequencies of ions rotating in a uniform magnetic field are measured and analysed by Fourier transform techniques. Sophisticated ionisation methods have been developed for the analysis of complex biomolecules and macromolecules.\textsuperscript{31}

**Aston’s later life**

Aston’s first mass spectrograph brought him immediate acclaim. He was appointed to a Fellowship in Trinity College, Cambridge in 1920 and was made a Fellow of the Royal Society in 1921. He was awarded the Nobel Prize in Chemistry in 1922 for, in the words of the citation, ‘his discovery, by means of his mass spectrograph, of isotopes in a large number of non-radioactive elements, and for his enunciation of the whole
number rule’. In proposing the toast of the laureates at a dinner in December of that year, Svante Arrhenius, the Director of the Nobel Institute, commented that never before had the Nobel Prize been handed over to a group of such distinguished laureates, which, besides Aston, included Niels Bohr, Albert Einstein, and Frederick Soddy. The last two were the 1921 prize winners in Physics and Chemistry respectively, but the awards were made in 1922.

Aston never married and for the last 35 years of his life lived in Trinity College. Outside his work his main interests were sport, travel and music. He was a keen cross-country skier, and played tennis up to tournament class. He played golf in a series of famous foursome with Ernest Rutherford, Ralph Fowler, and Geoffrey (G. I.) Taylor. He was an enthusiastic cyclist, once cycling 200 miles in 22 h. He was also an excellent photographer and combined this hobby with his love of travel to help at several solar eclipse expeditions. He was an omnivorous reader, Sherlock Holmes being his favourite. An acquaintance once described him as the highest lowbrow that he had ever met.

Aston died on 20 November 1945. In an obituary in Nature11 G. P. Thomson wrote ‘Aston was a man in whom a great zest for life was combined with a simplicity of character almost approaching naivety. Though a good occasional lecturer, he had no gift for teaching, and a few early attempts were not persisted in. His attitude to physics was essentially that of the experimenter and visualizer. He preferred the model to the equation, the concrete to the abstract. He was a Conservative in politics as in life, and though he would admit that a change persisted in. His attitude to physics was essentially that of the

Acknowledgements

Fig. 8 is reproduced from the Philosophical Magazine, 1920, by permission of Taylor & Francis. Figs. 5 and 9 to 12 are from the Photographic Archives of the Cavendish Laboratory.

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29 The term mass spectrometer is reserved for an instrument that records the spectra on a photographic plate, an instrument that employs electrical detection being termed a mass spectrometer. The last reported use of a mass spectrometer was in 1972.
30 Ref. 28, p. 159.
33 Ref. 10, p. 139.